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Burger et al.

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(54) **ADSORPTION CELL, ADSORPTION CLUSTER AND ADSORPTION COMPRESSOR AS WELL AS METHOD OF OPERATING AN ADSORPTION COMPRESSOR**

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(73) Assignee: **Cooll Sustainable Energy Solutions B.V.**, Enschede (NL)

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(51) **Int. Cl.**
*F25B 25/02* (2006.01)
F25B 17/08 (2006.01)
F25B 35/04 (2006.01)

(52) **U.S. Cl.**
CPC *F25B 25/02* (2013.01); *F25B 17/08* (2013.01); *F25B 35/04* (2013.01); *Y02B 30/64* (2013.01)

(58) **Field of Classification Search**
CPC F25B 25/02; F25B 17/08; F25B 35/04; F25B 2315/00; F25B 35/0462; Y02B 30/64
See application file for complete search history.

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(57) **ABSTRACT**

An adsorption cell suitable for a thermal wave operated adsorption compressor comprising an elongated solid adsorption material extending along an axis, the elongated solid adsorption material and an elongated heat transfer fluid (HTF) channel in direct heat transferring contact with the outside surface of the solid adsorption material. The adsorption material is formed by a stack of units, i.e. pills of adsorption material. Each pill is accommodated in an associated cup from a heat conductive material. The surface conformity and roughness of the bottom of pill of the unit and of top of the pill of the adjacent unit on the one hand and of the cup bottom wall on the other hand are such that any gap between the abutting bottom and cup bottom wall and the abutting top and cup bottom wall is less than 30 micron, preferably less than 10 micron.

21 Claims, 31 Drawing Sheets
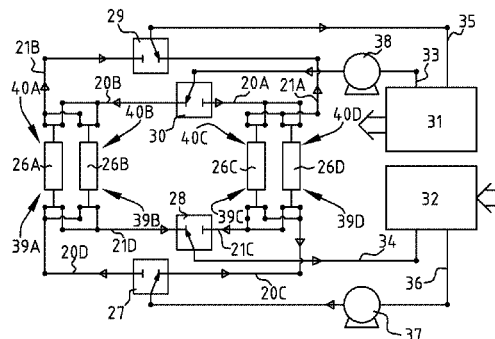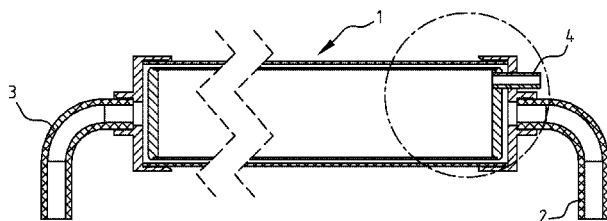
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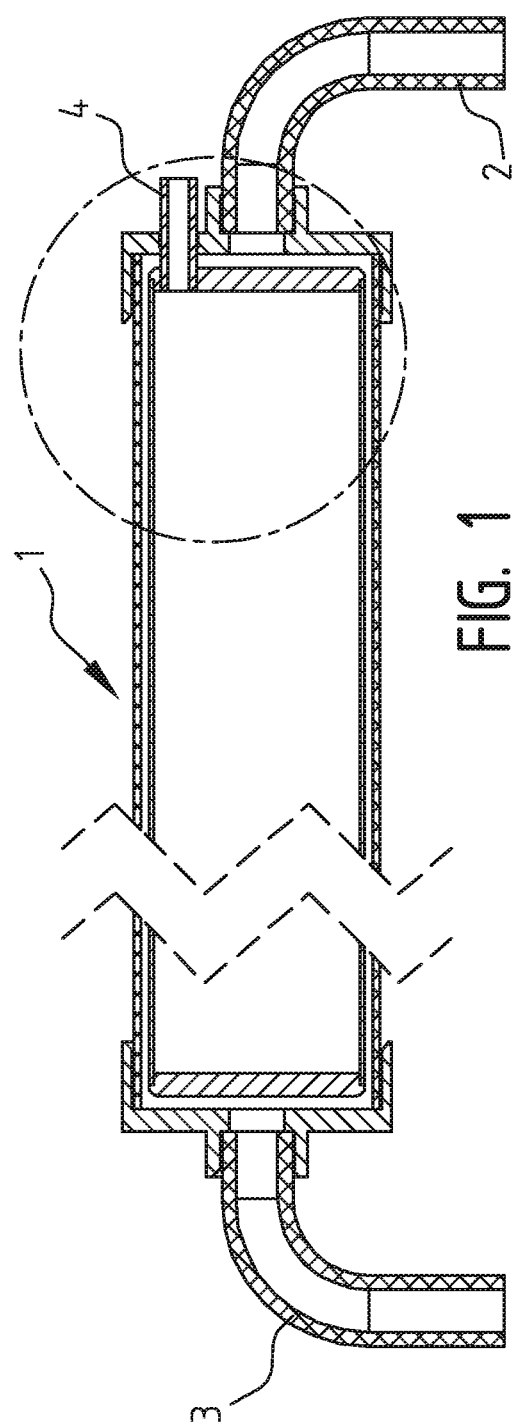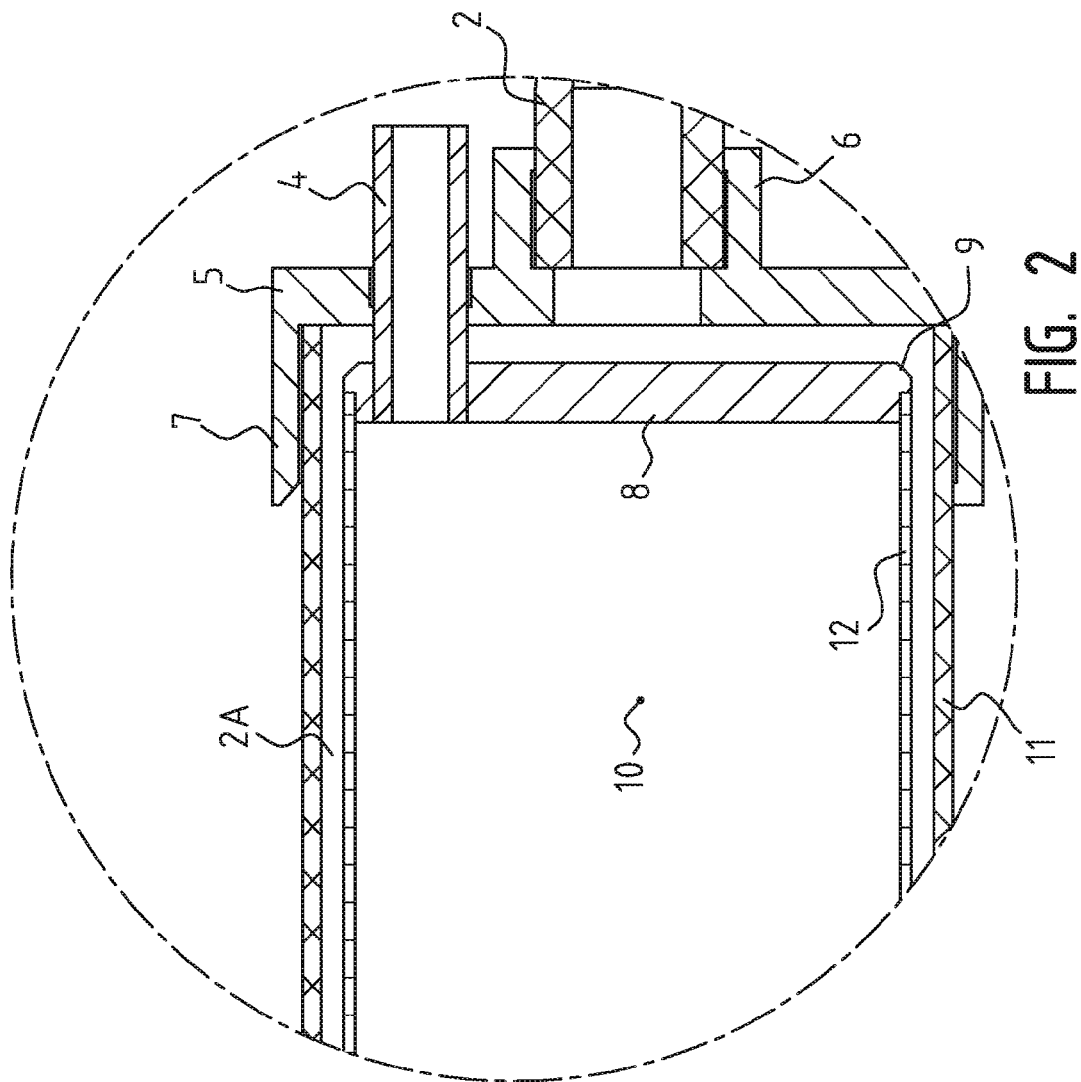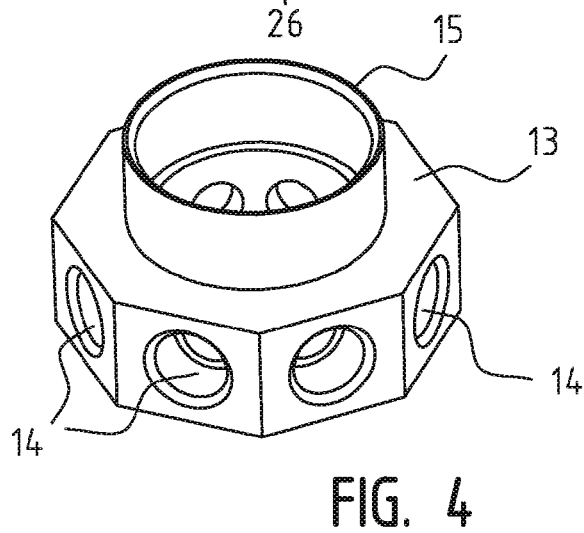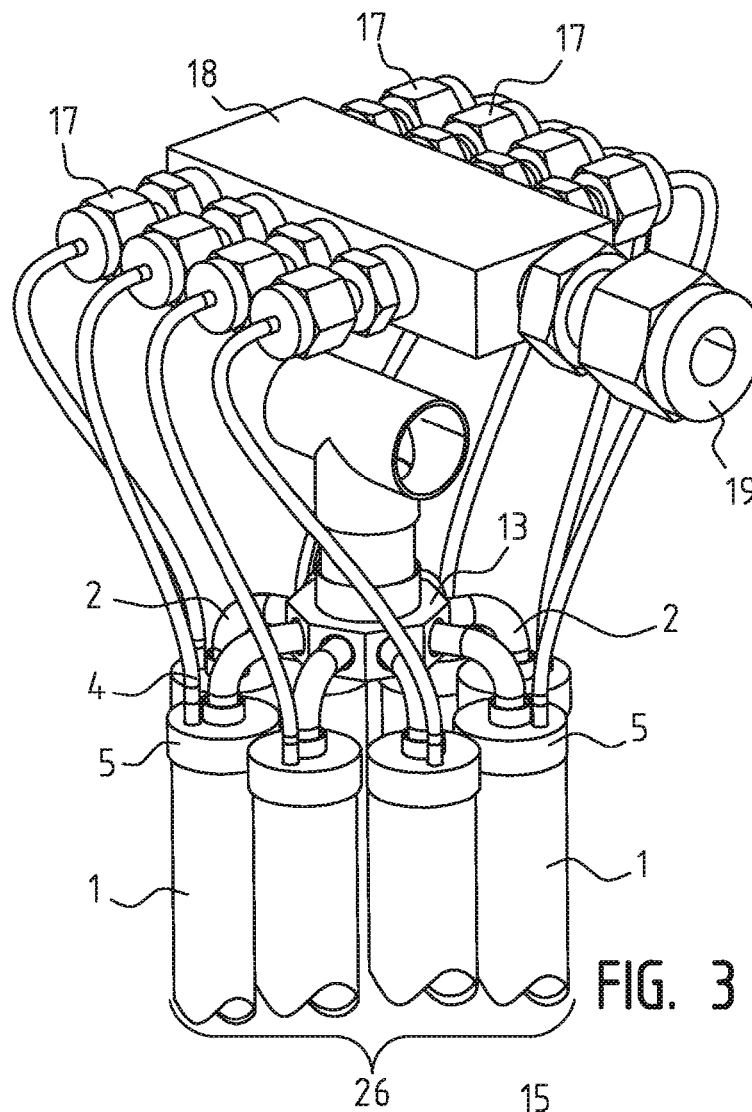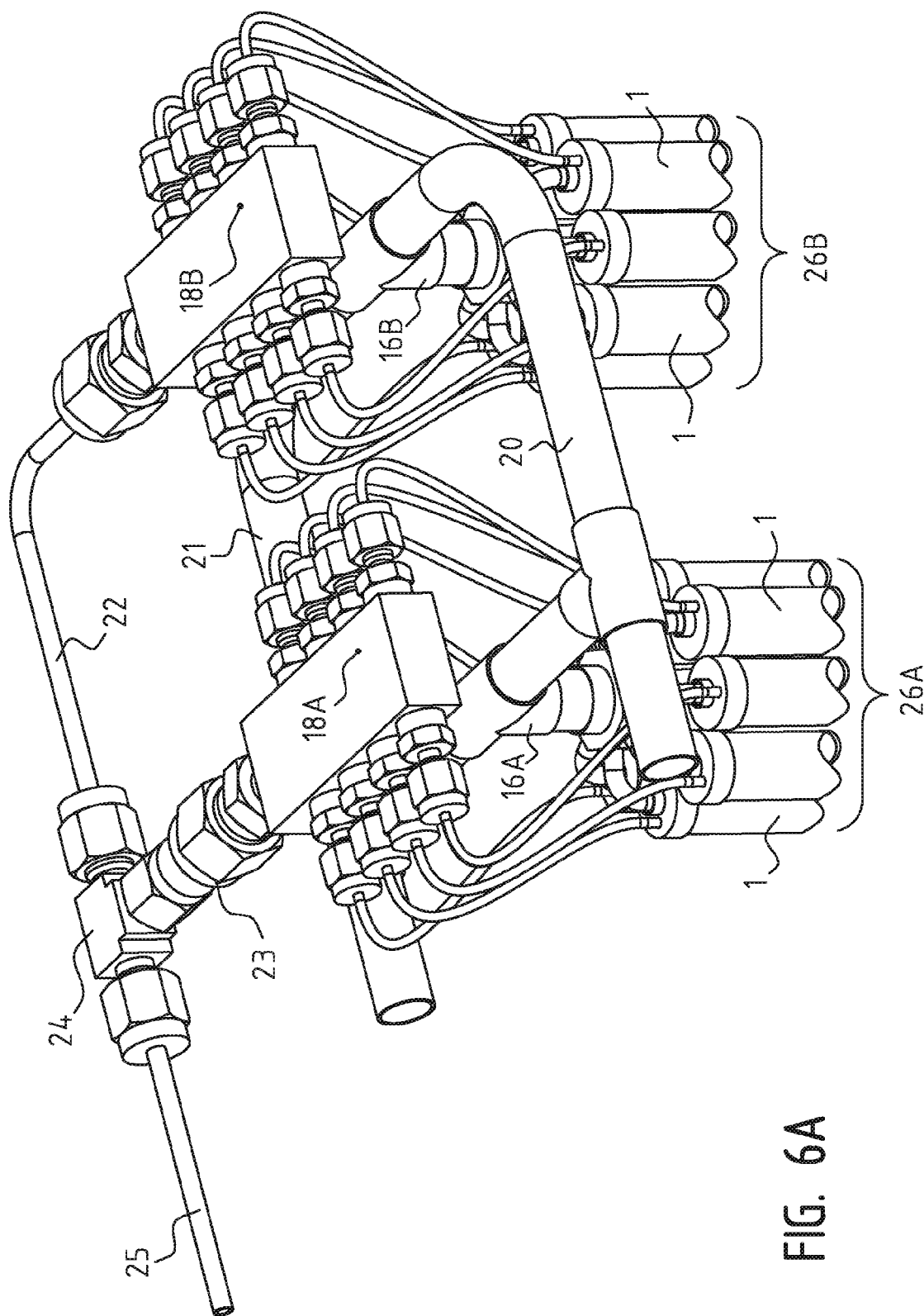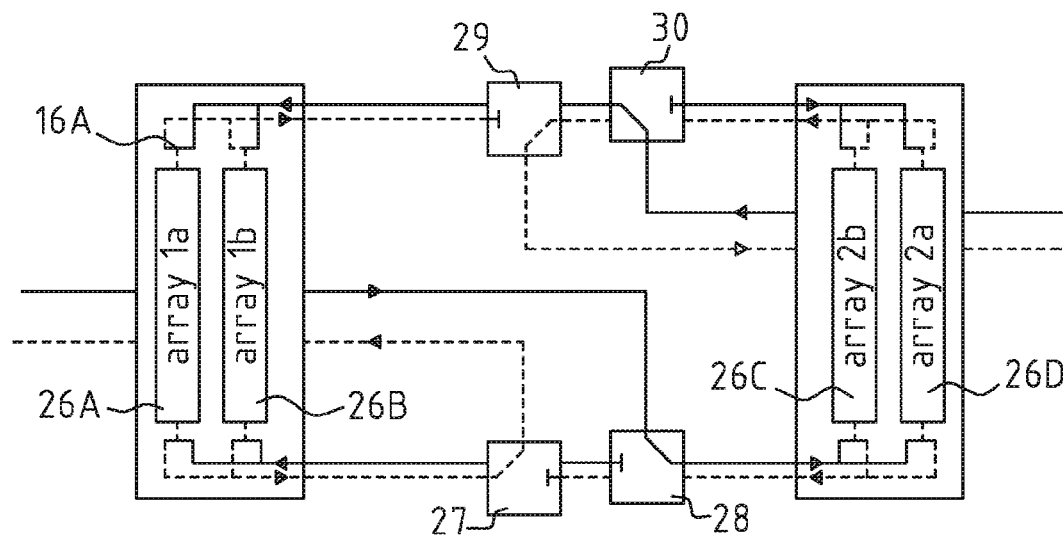
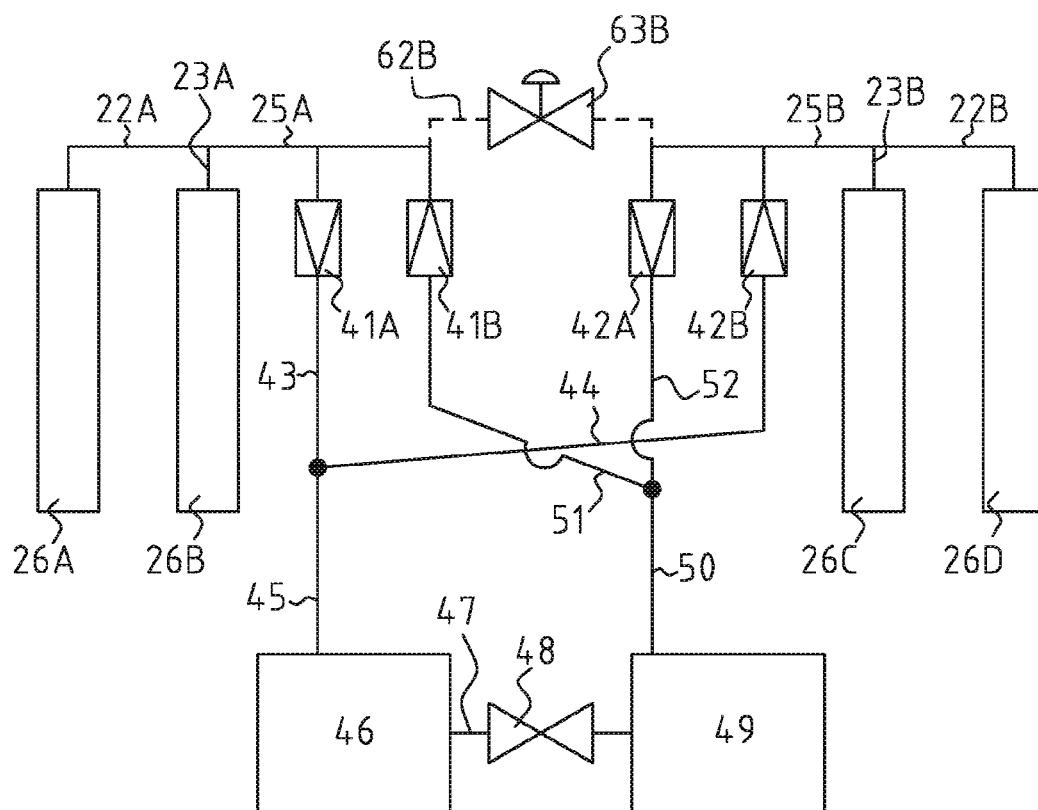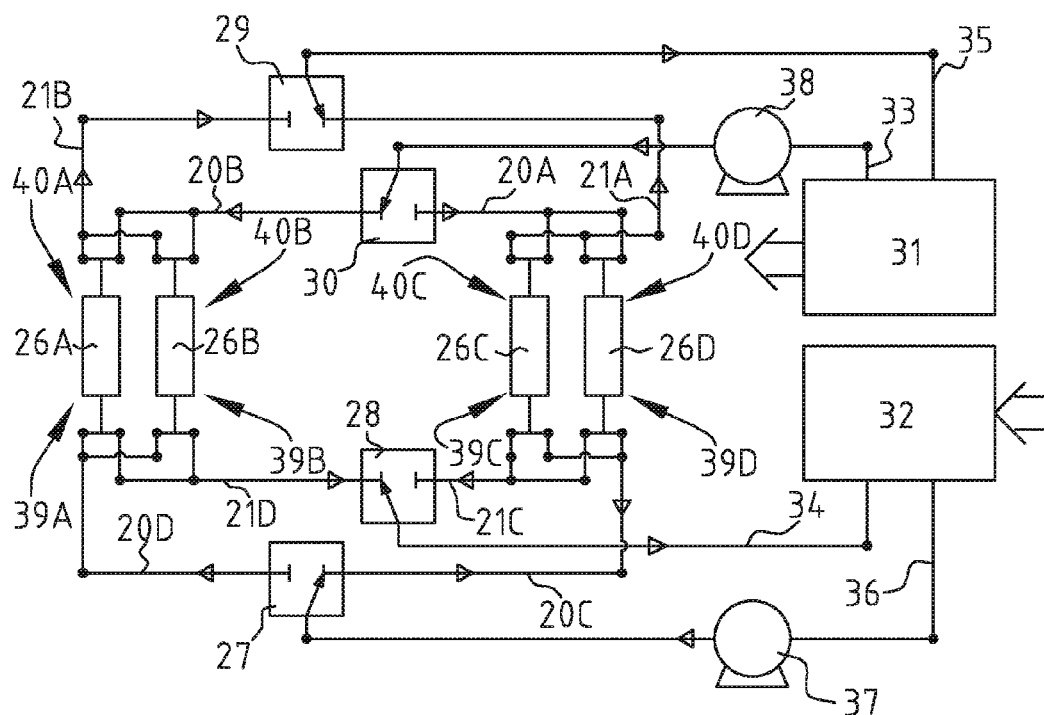* cited by examiner

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6A
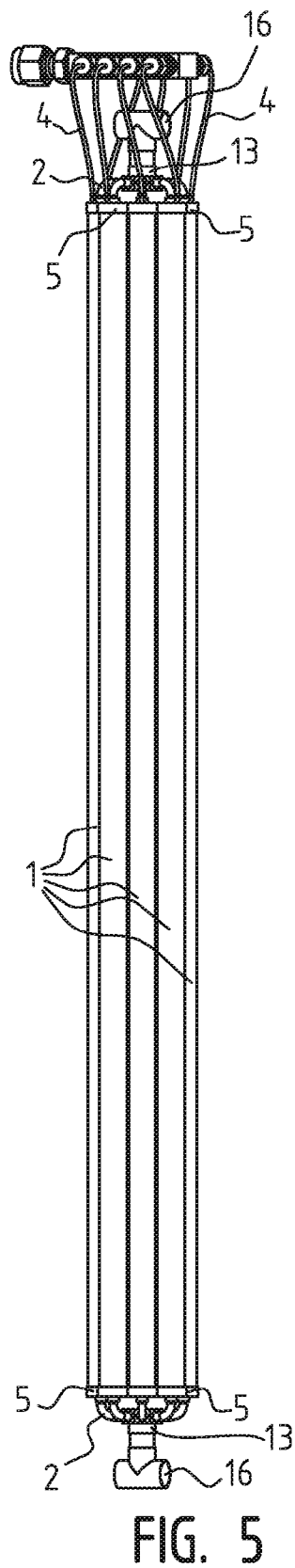
FIG. 6B

FIG. 9

FIG. 7
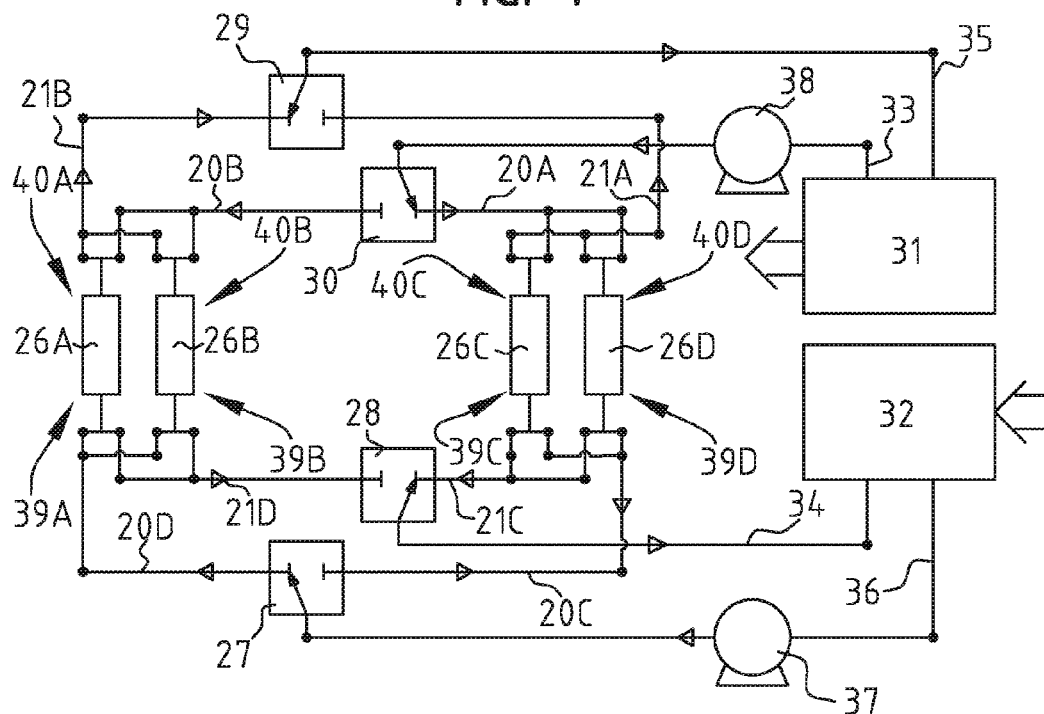
FIG. 8

FIG. 10A

FIG. 10B
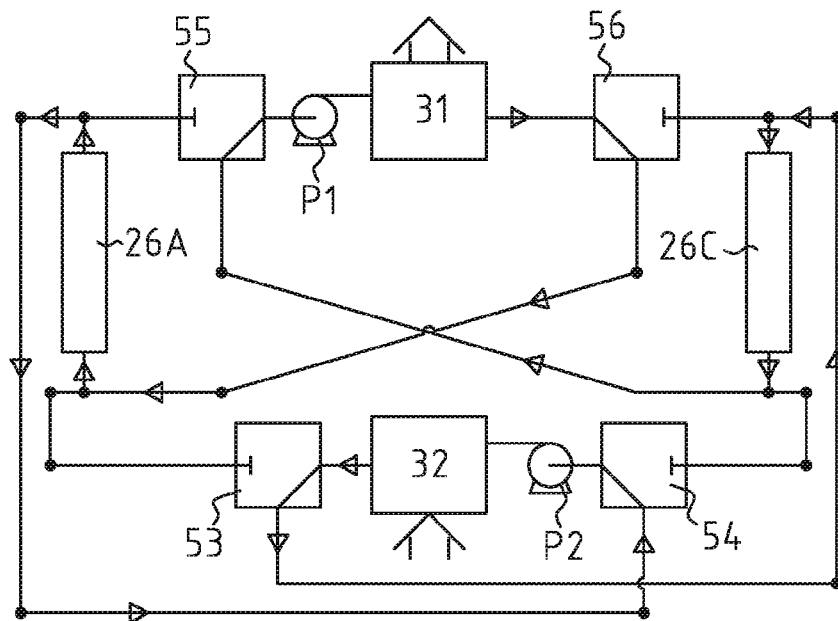
FIG. 10C
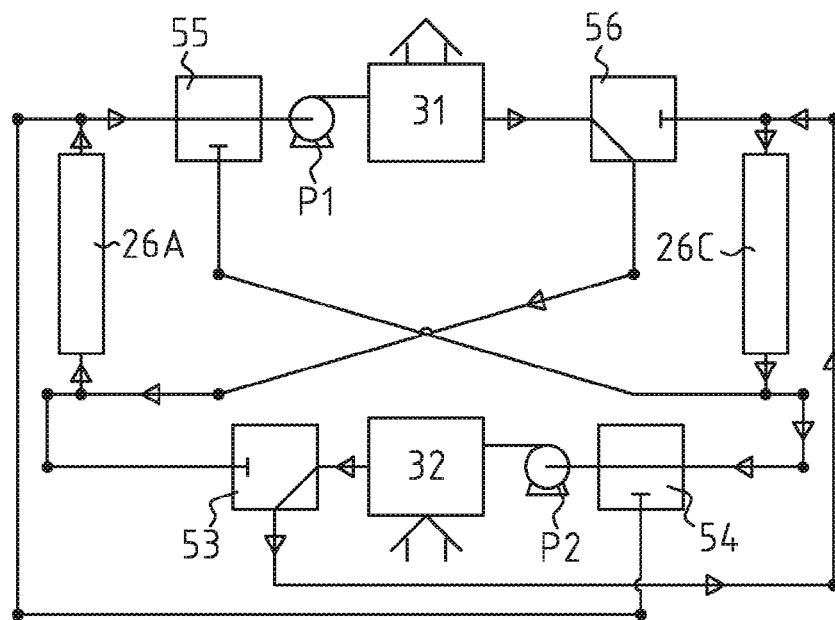
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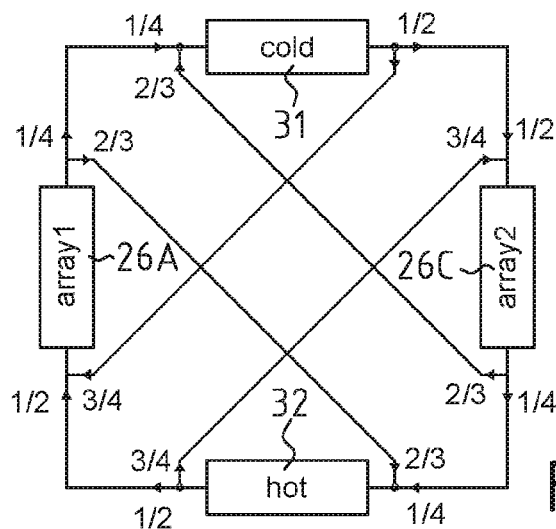
FIG. 10E
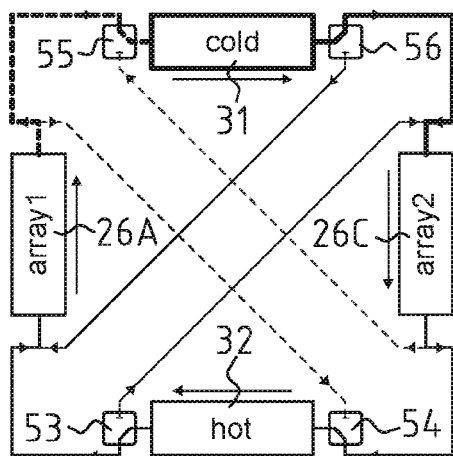
FIG. 10F
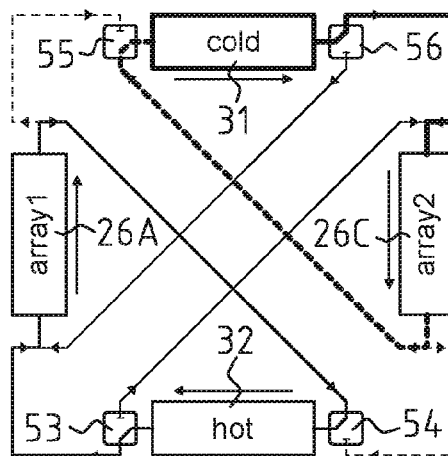
FIG. 10G

FIG. 10H

FIG. 10I

FIG. 11A

FIG. 11B

FIG. 11C

FIG. 11D

FIG. 12

FIG. 13

FIG. 14

12   12   12

11

10   11

FIG. 16

12   11   10

10

12   11

FIG. 17

W_{HTF}

61

10   12   11

FIG. 15

70

62A

69   69

68B   70

62A

70

FIG. 18B

10

68B

62A

62

62A

62A

70   62A

FIG. 18A

FIG. 19

FIG. 21D

FIG. 21C

FIG. 21B

FIG. 21A

FIG. 20
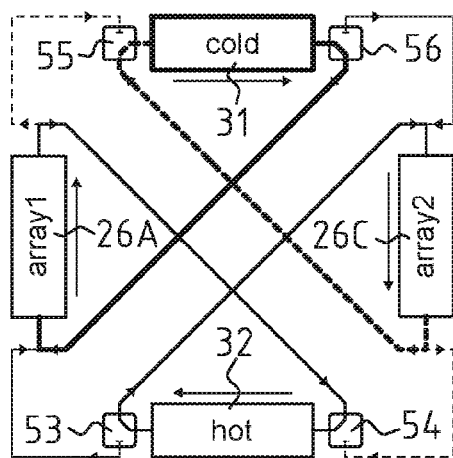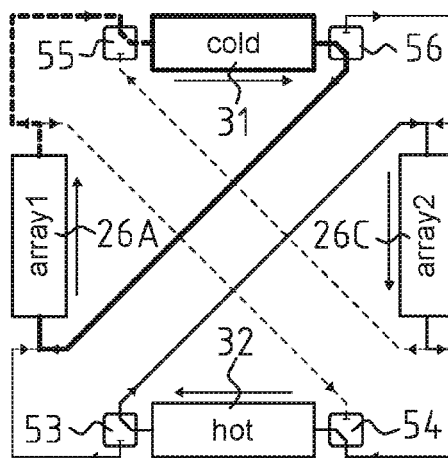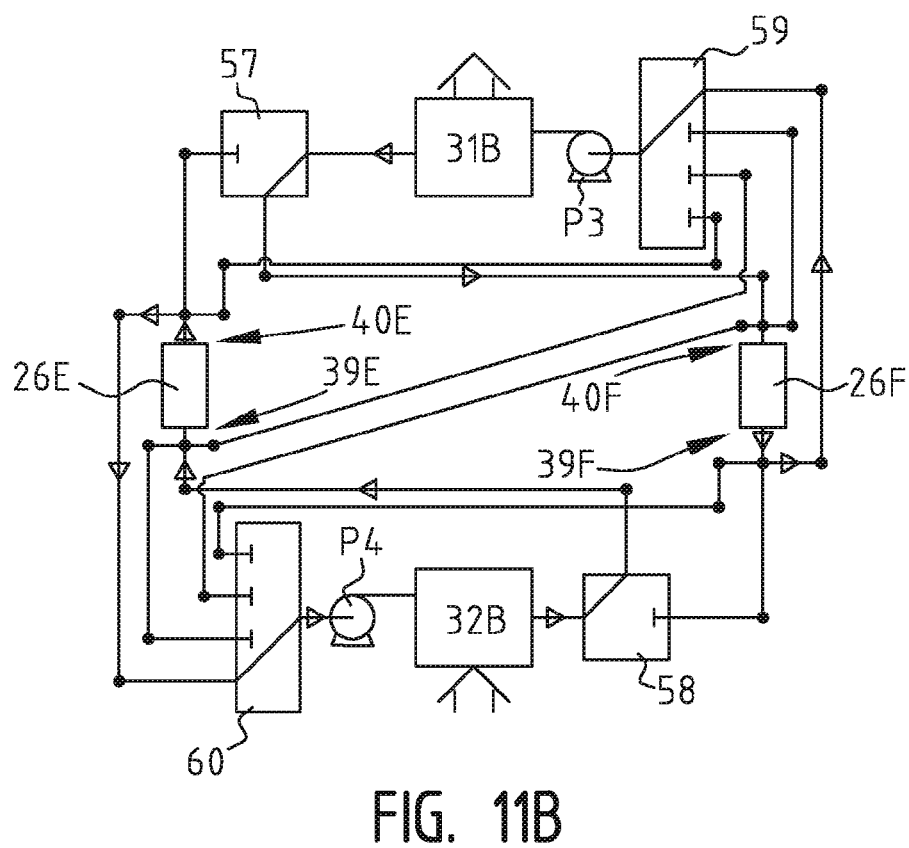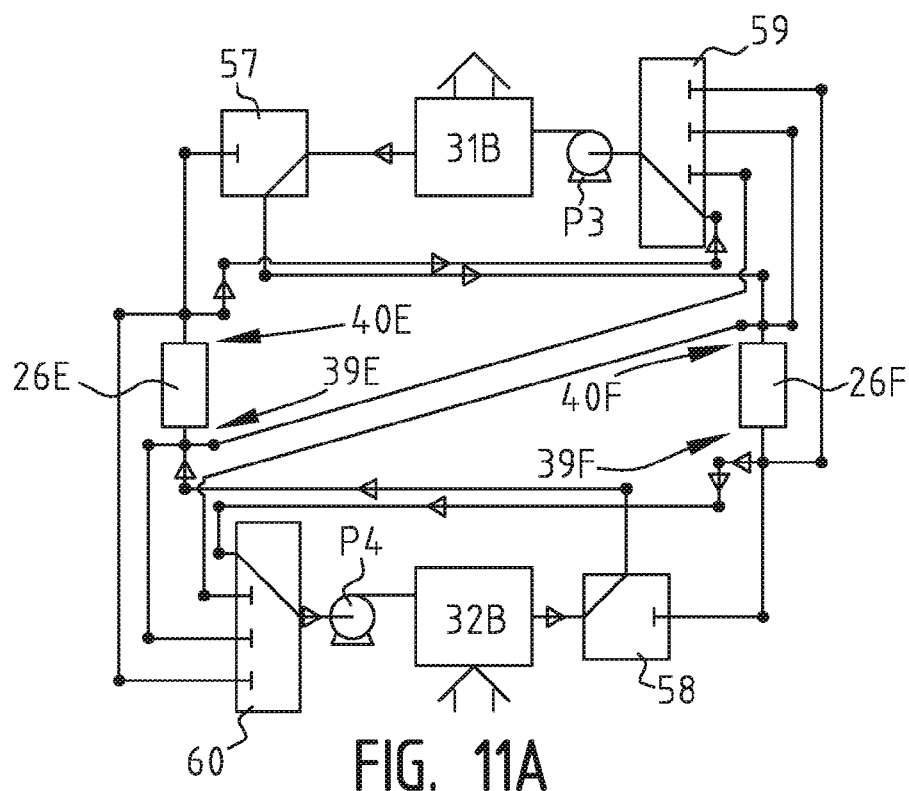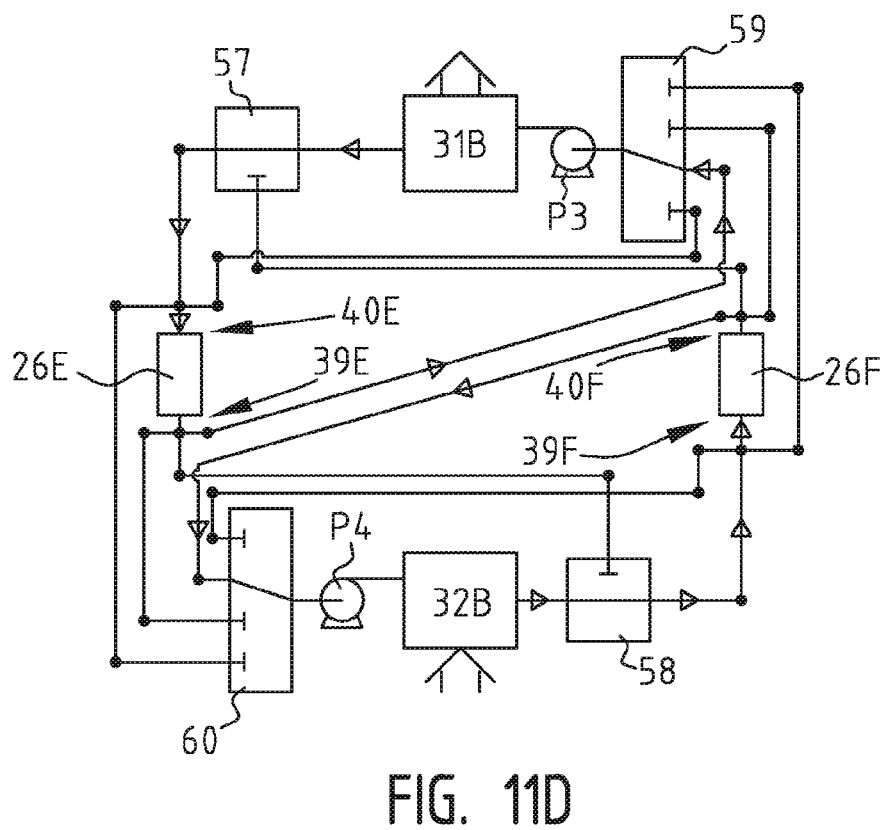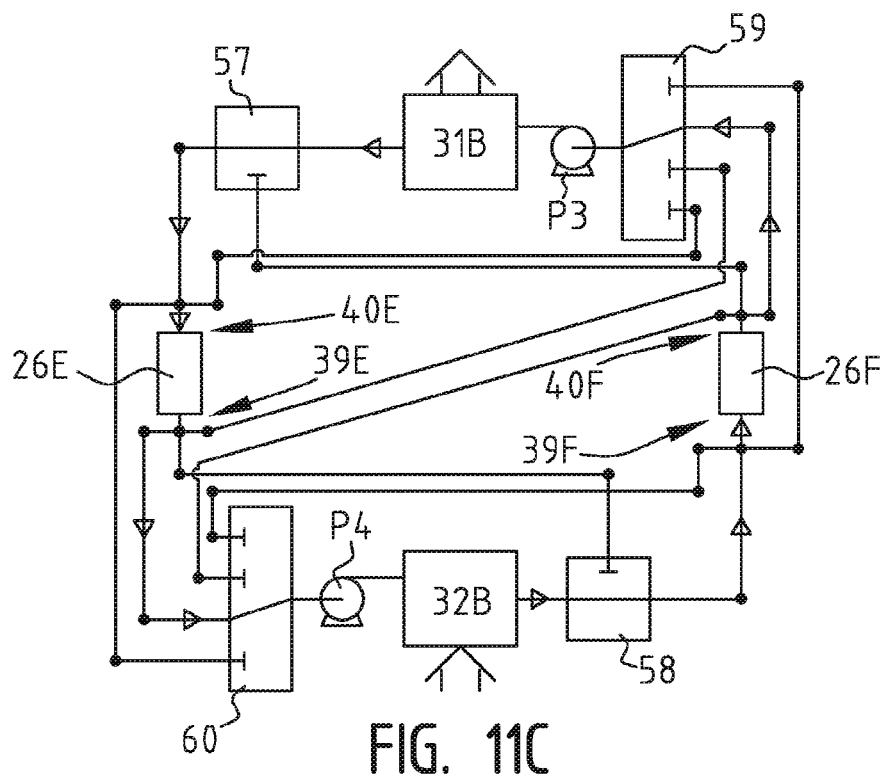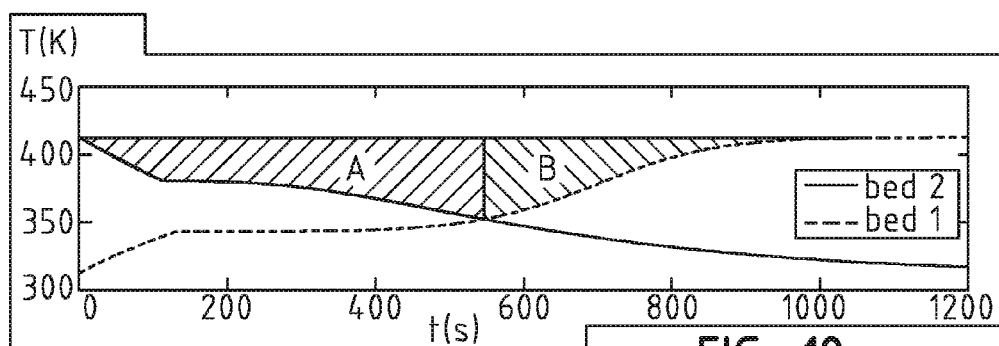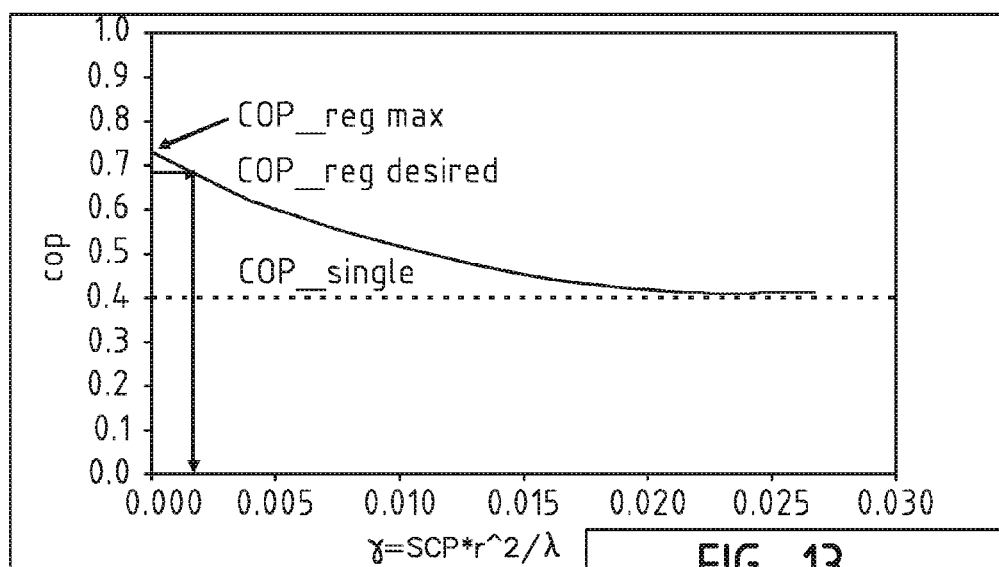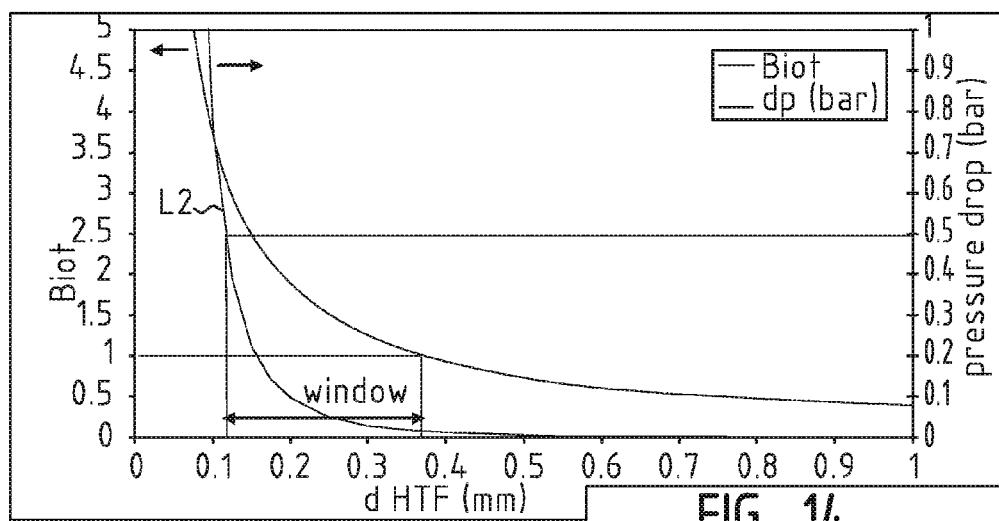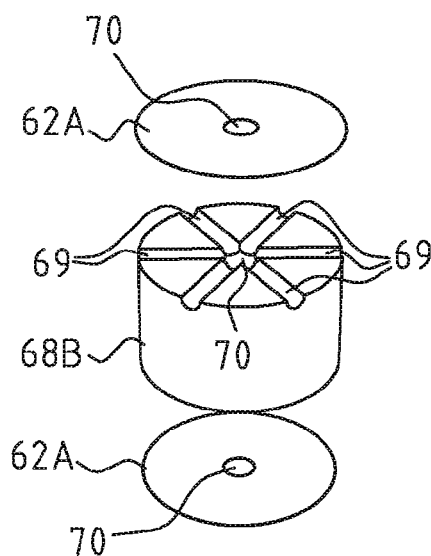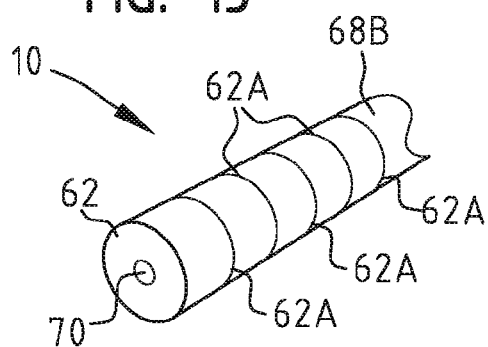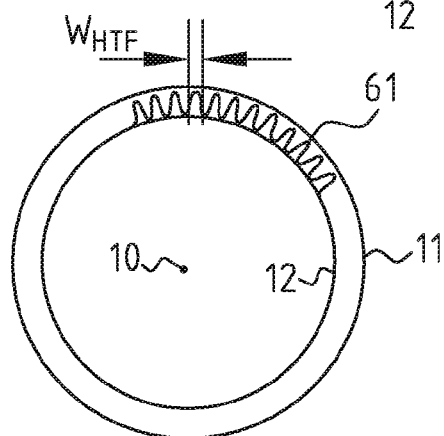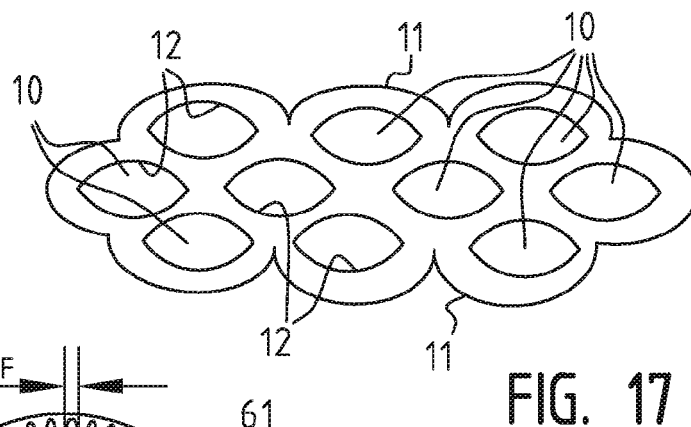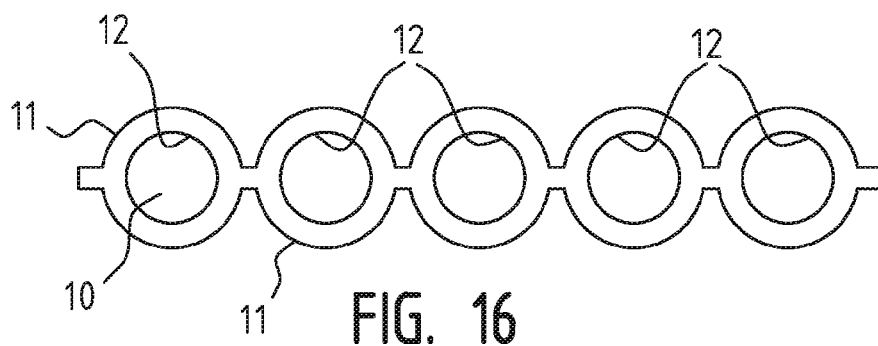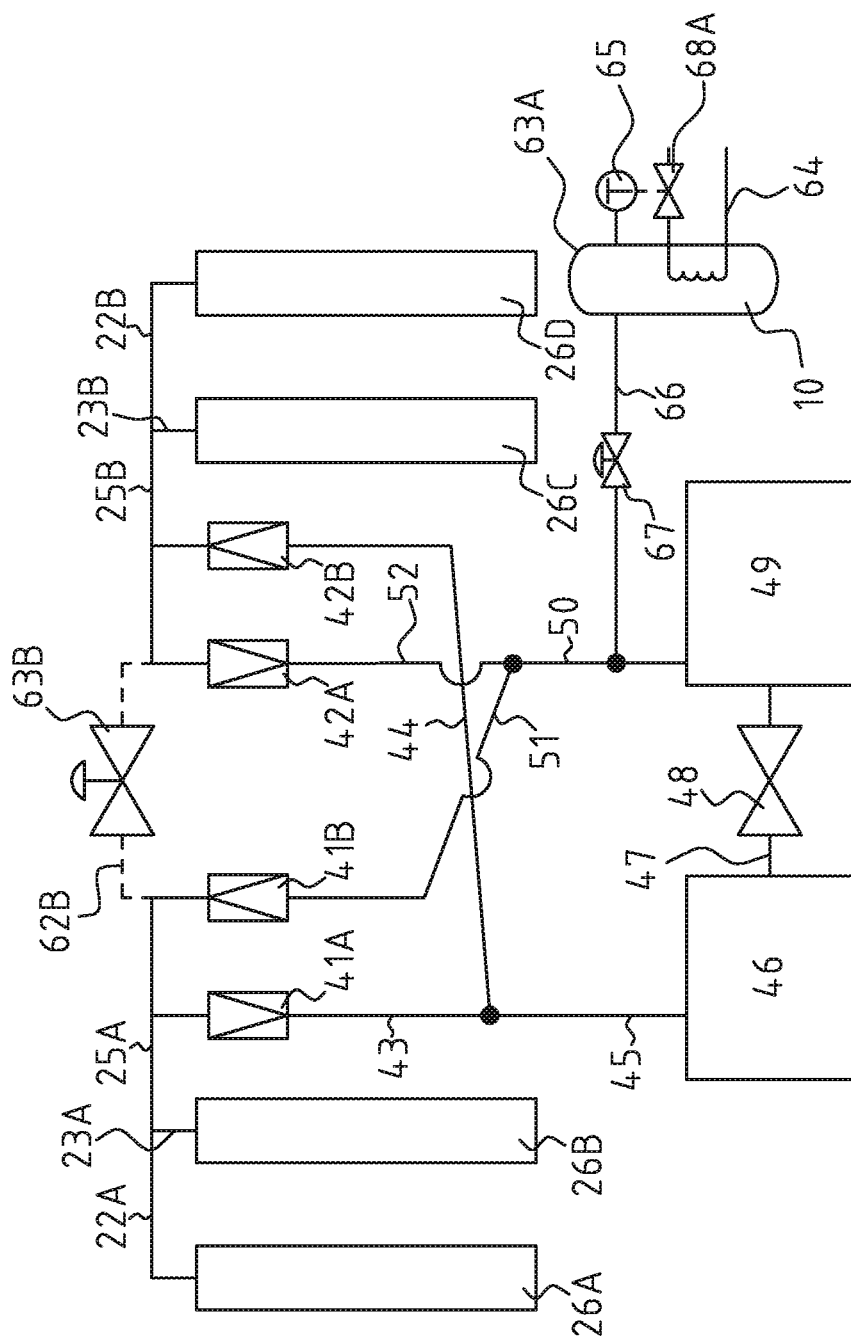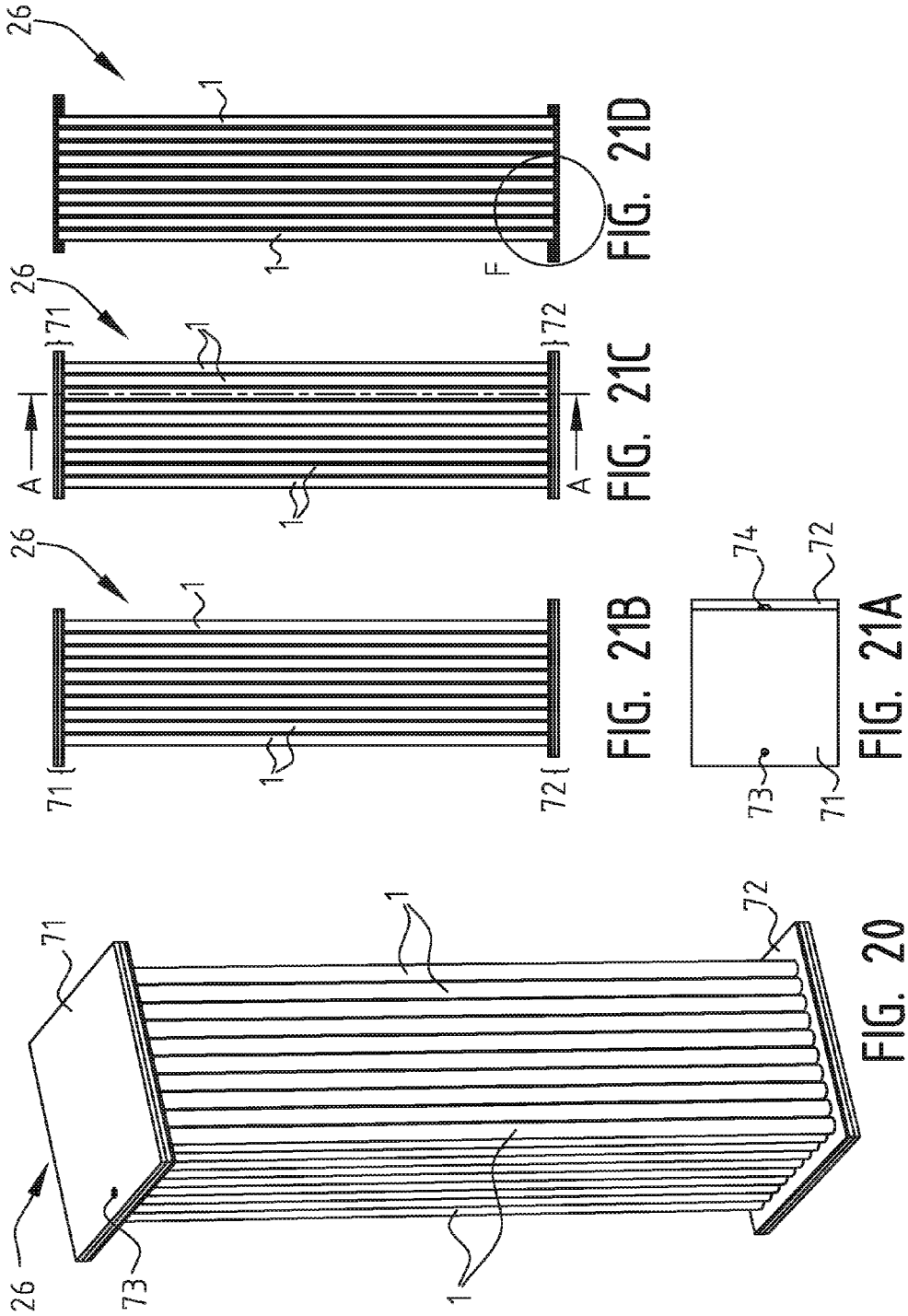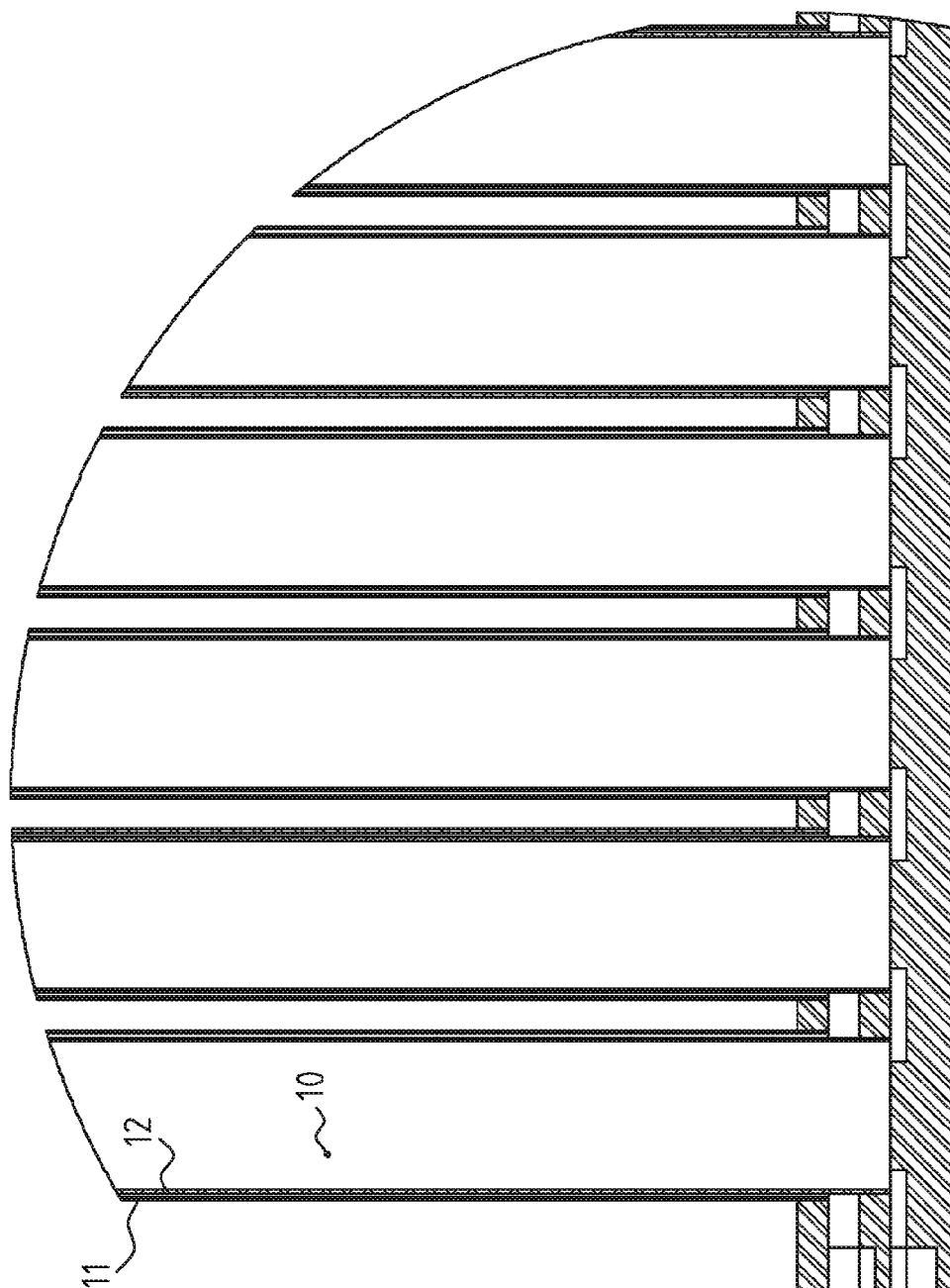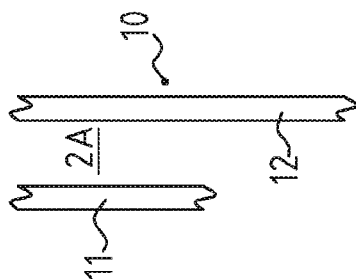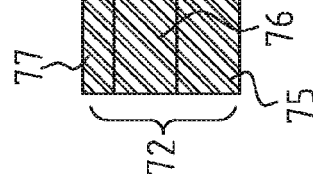
FIG. 21E

FIG. 21F
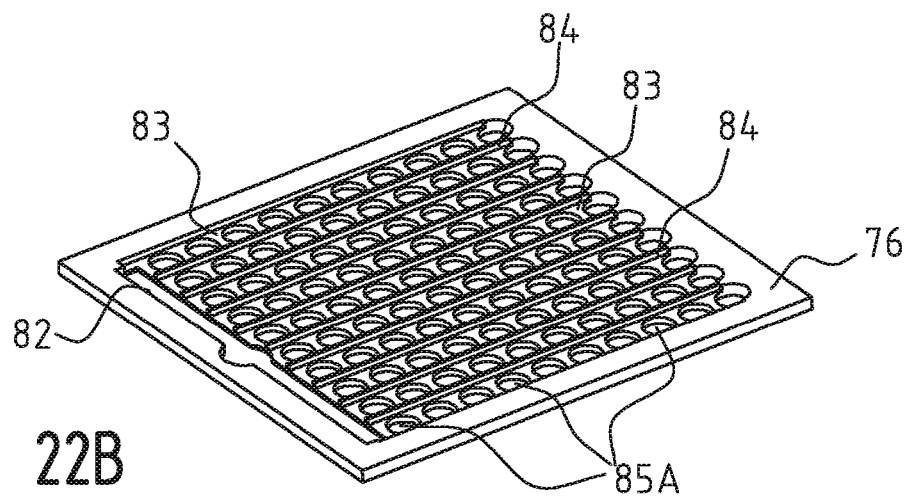
FIG. 22A

FIG. 22B

FIG. 22C
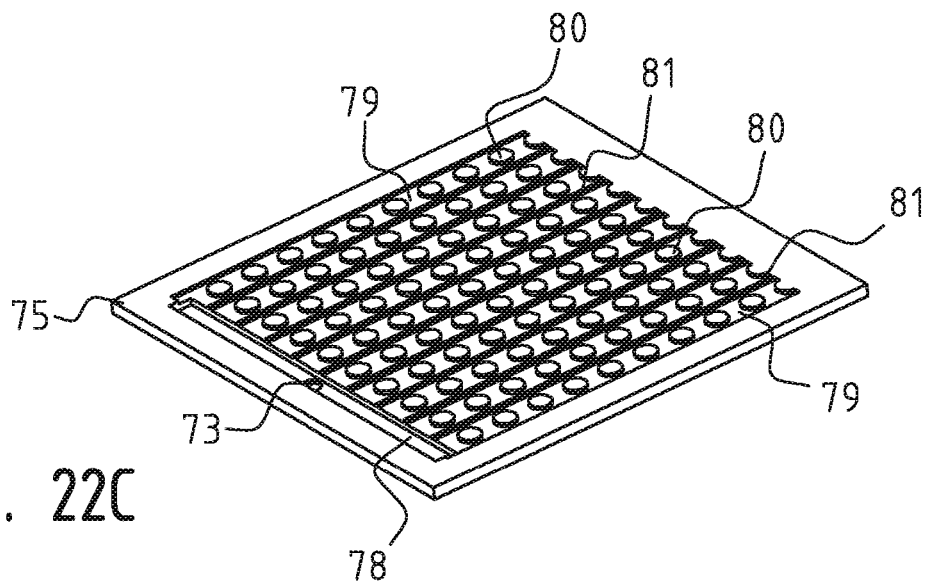
FIG. 23B

FIG. 23A

FIG. 24
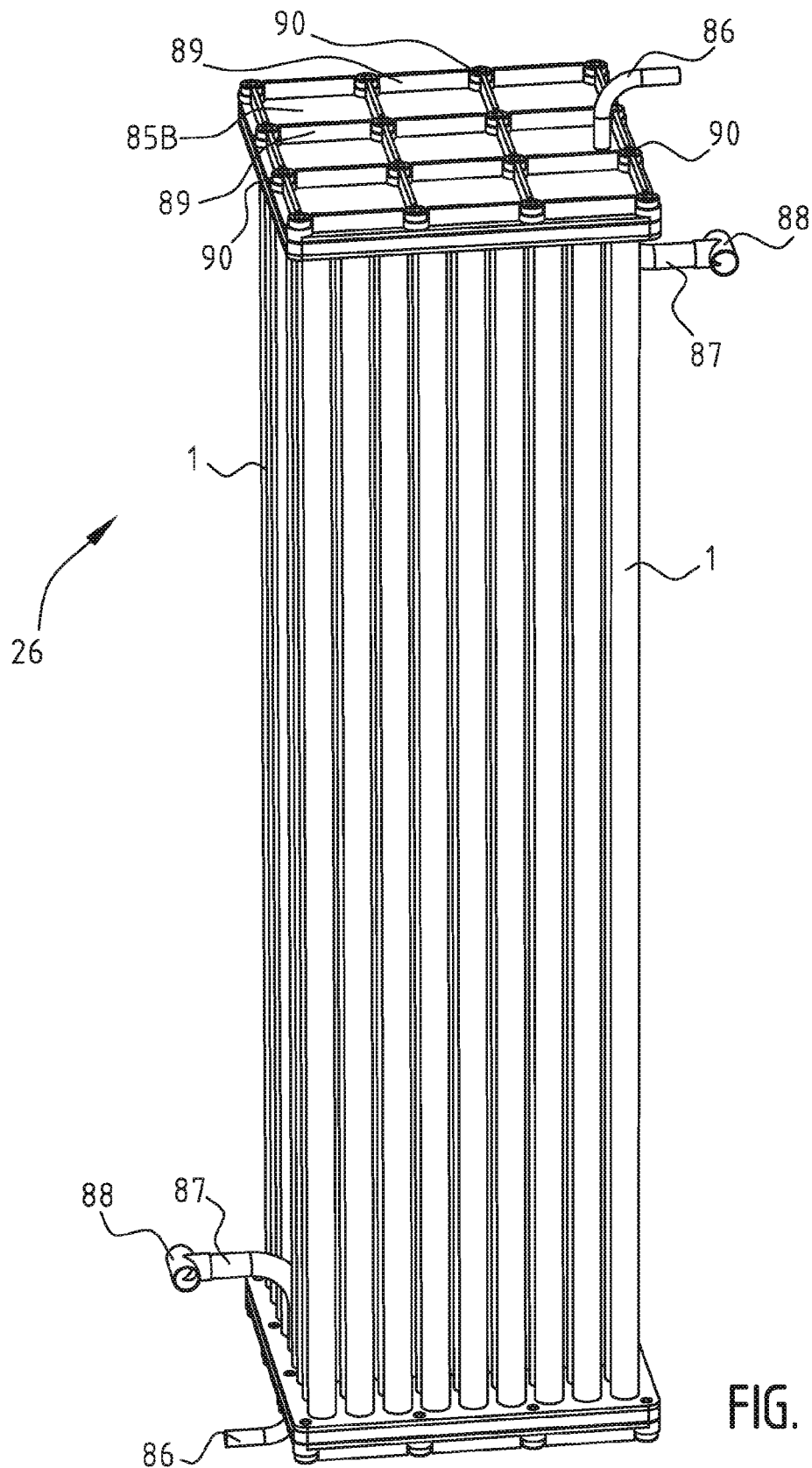
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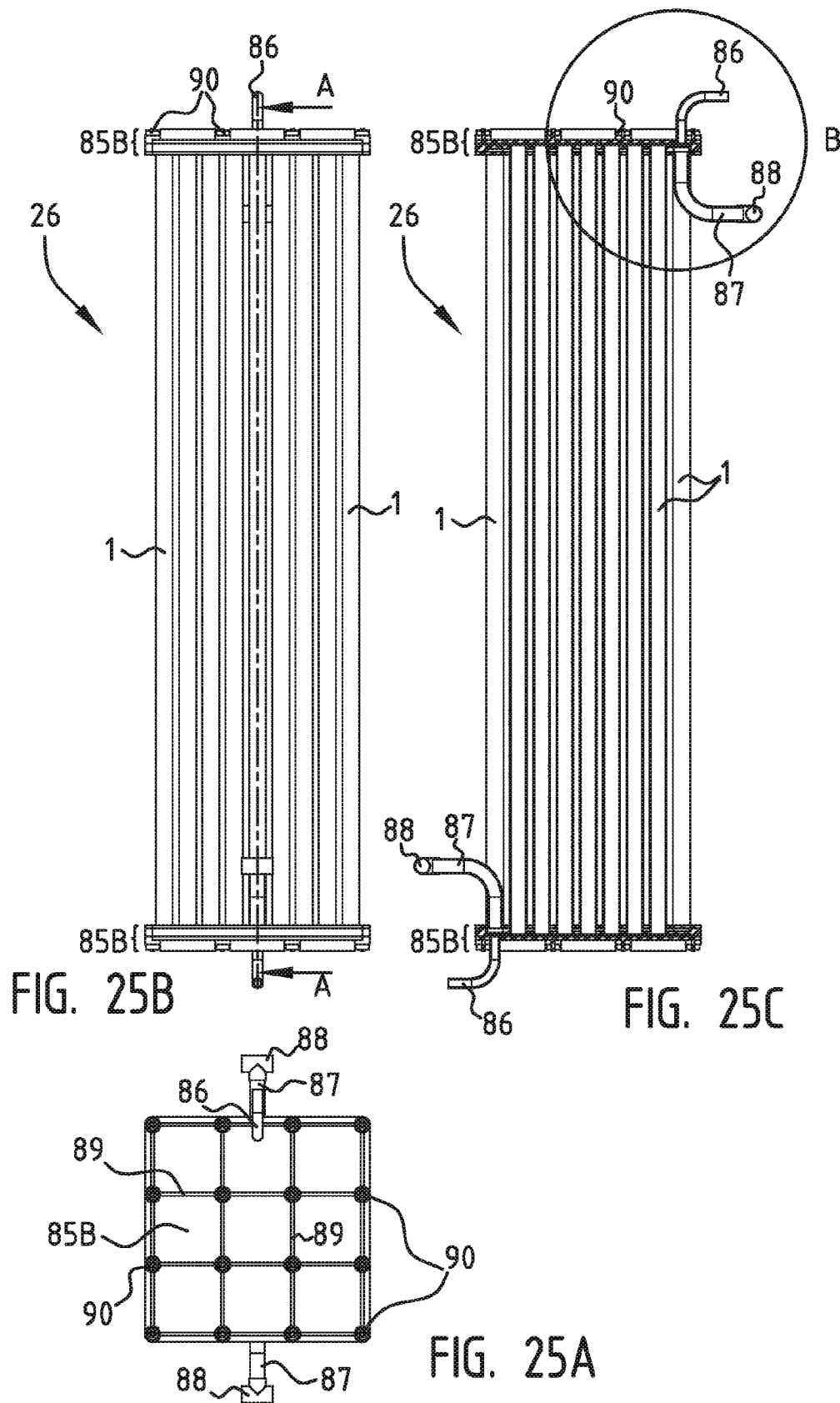
FIG. 25C

FIG. 25A

FIG. 25D

FIG. 26A

FIG. 26B
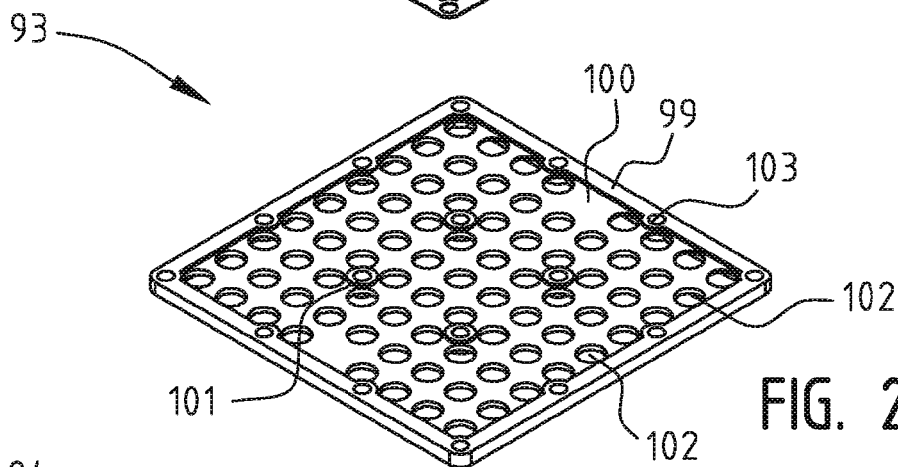
FIG. 26C

FIG. 26D
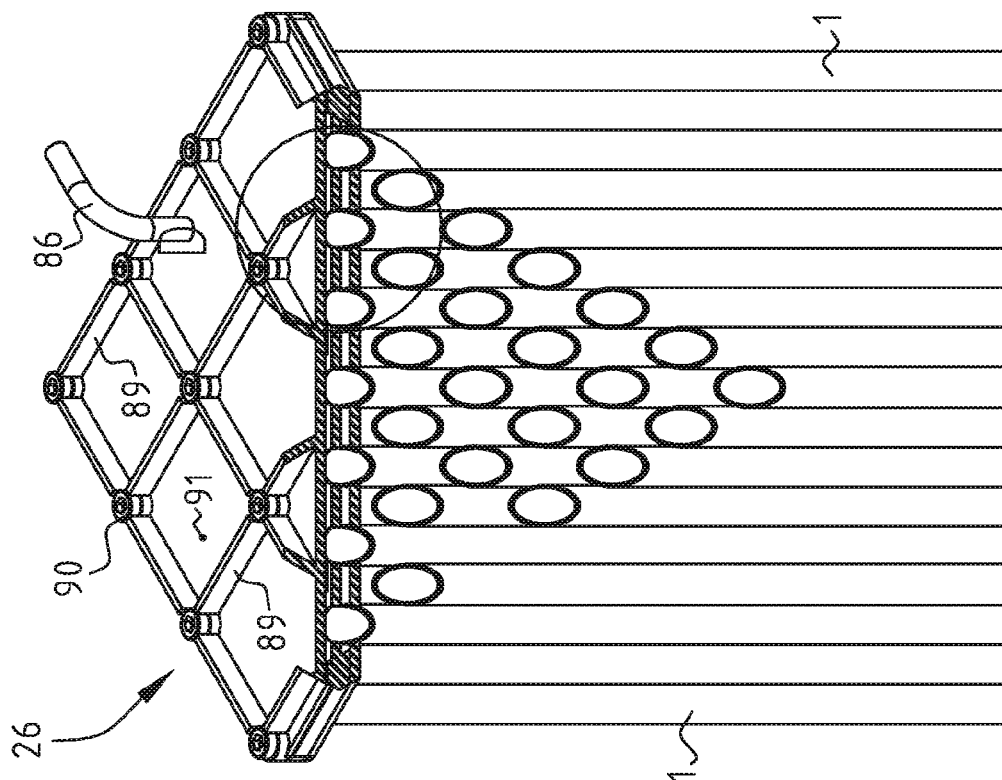
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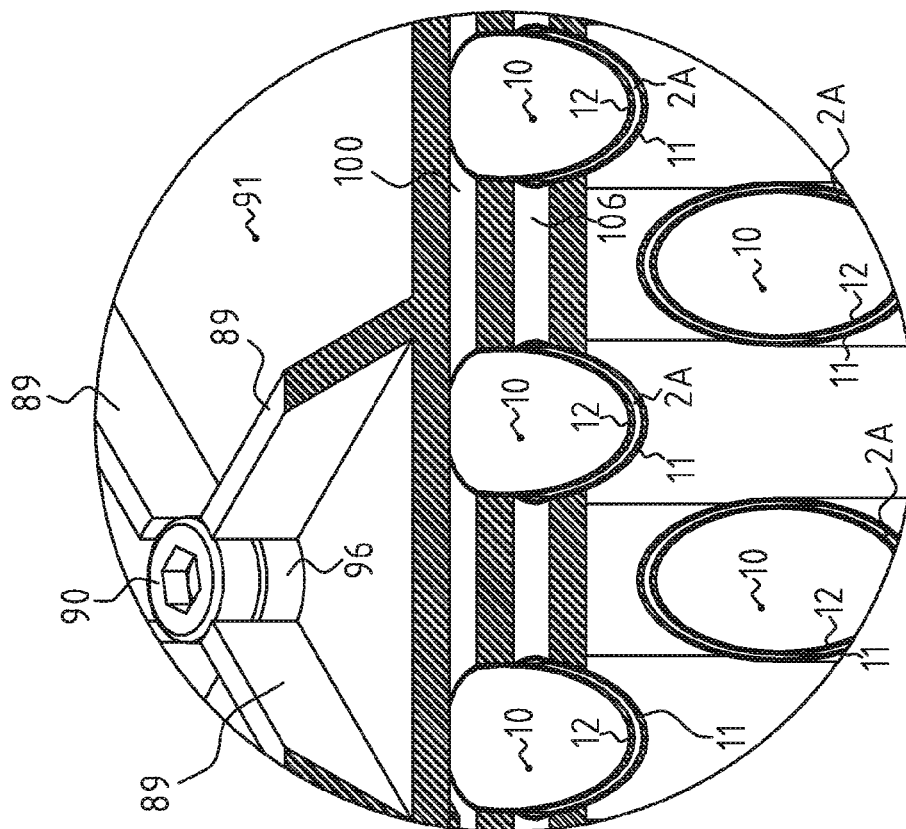
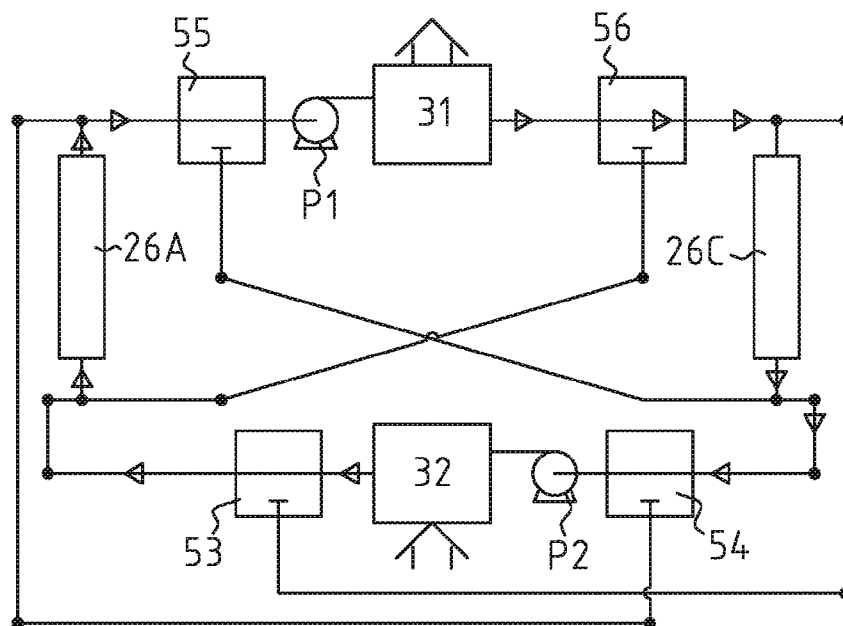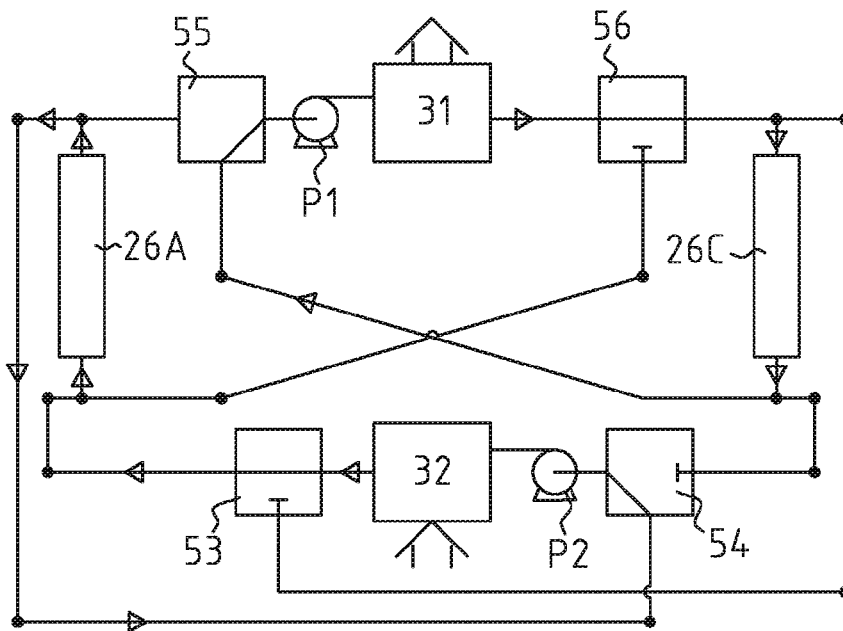FIG. 27A
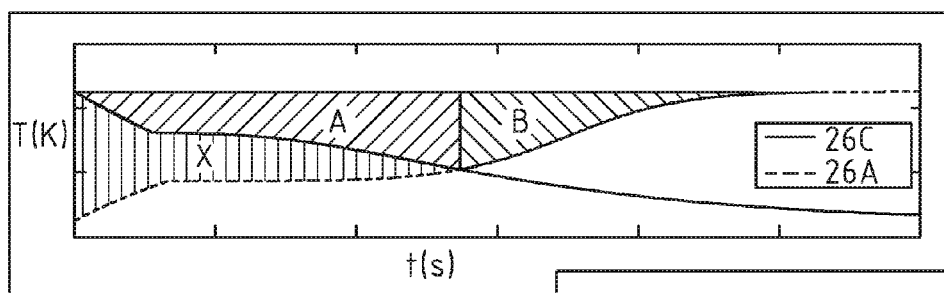
Fig. 28
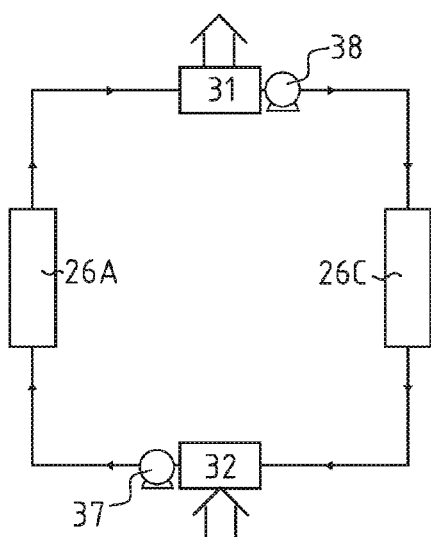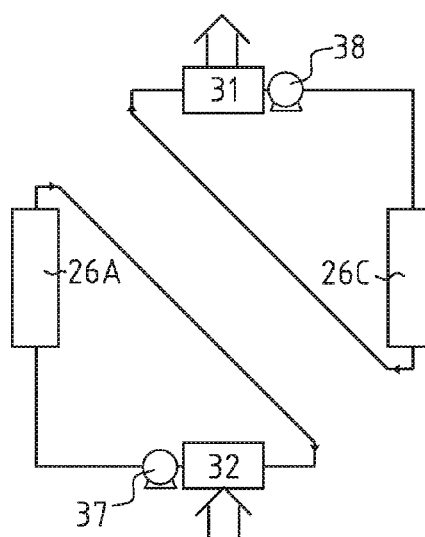
Fig. 29A

Fig. 29B
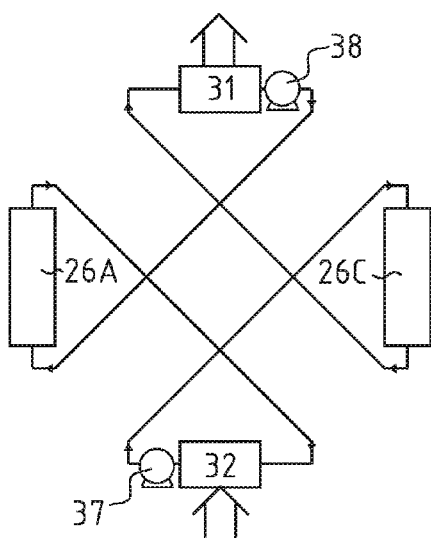
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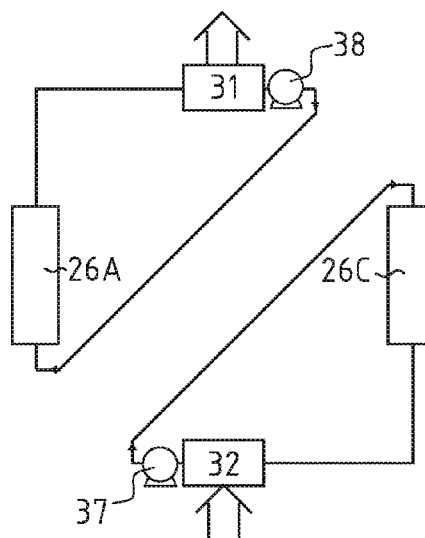
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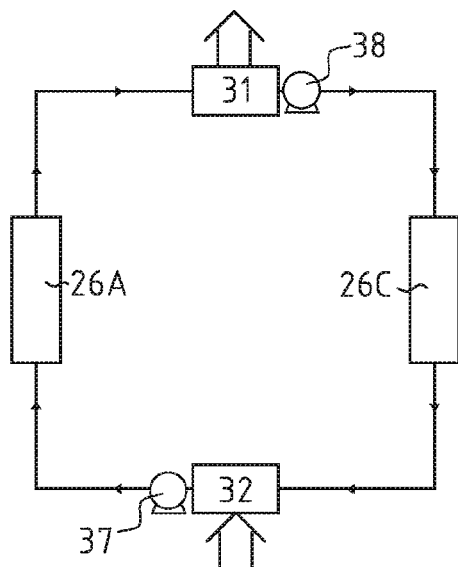
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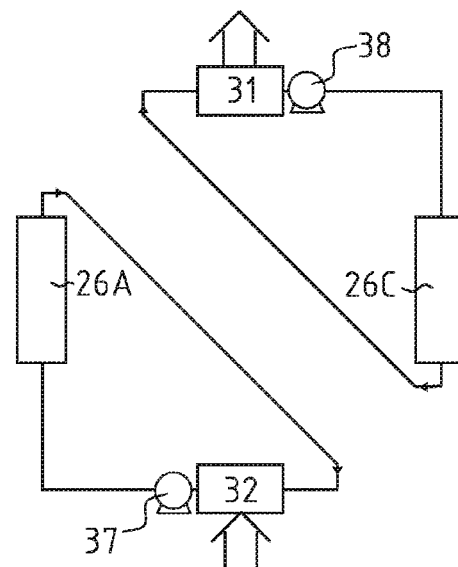
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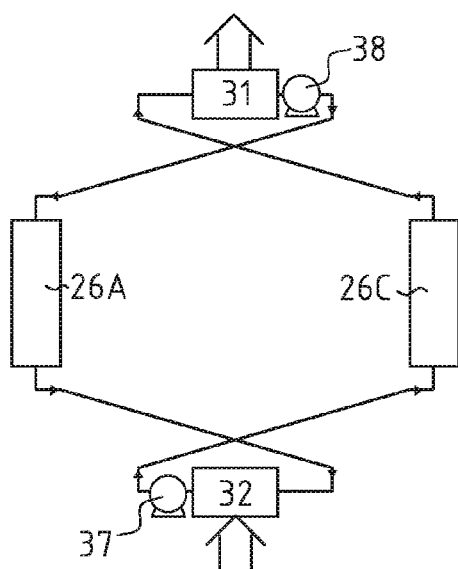
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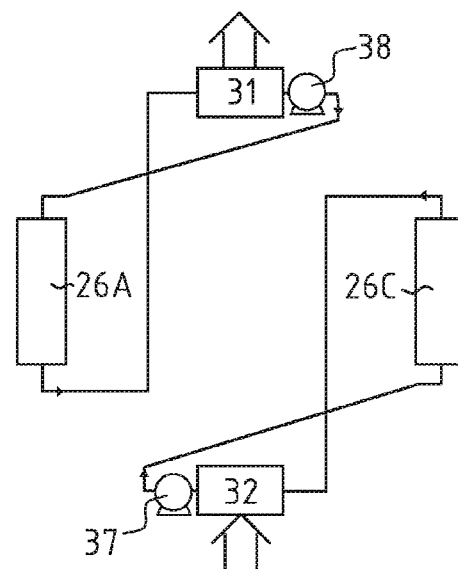
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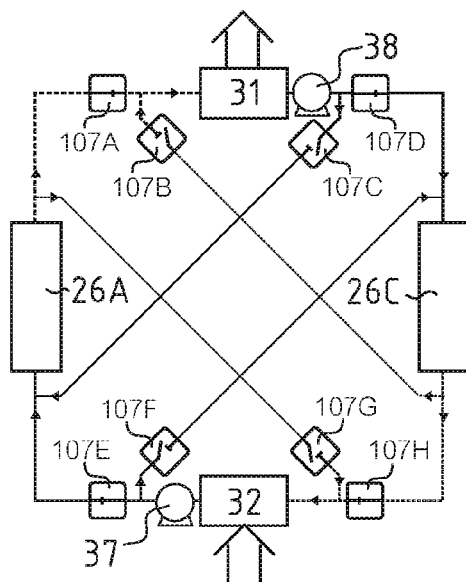
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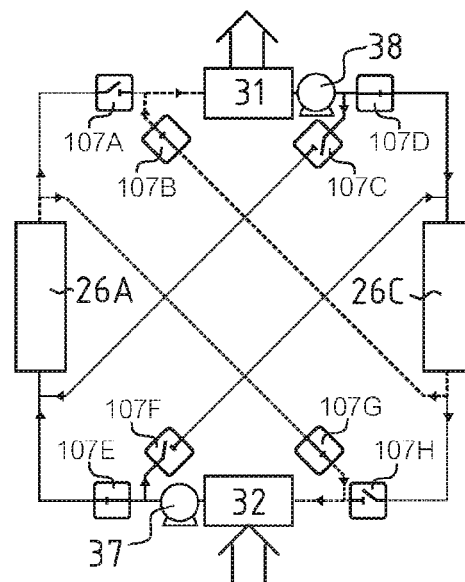
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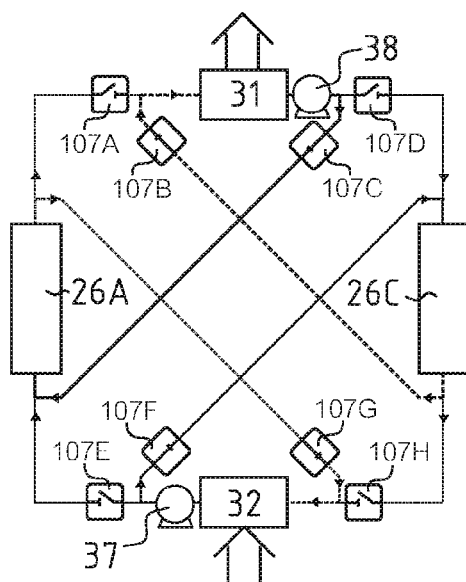
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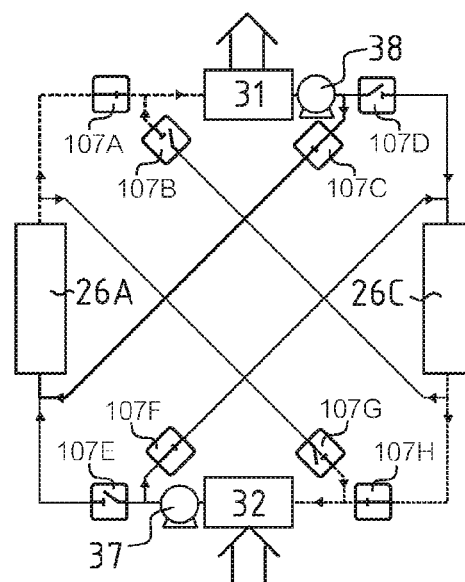
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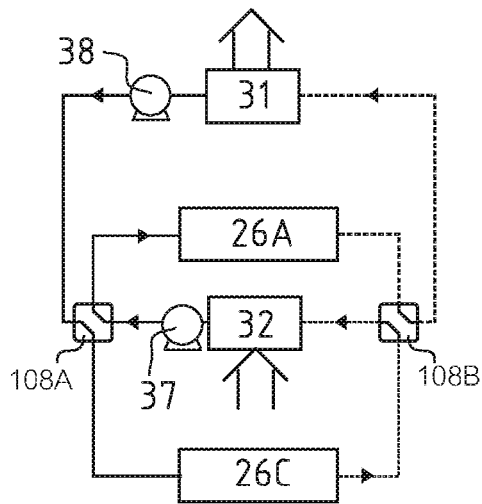
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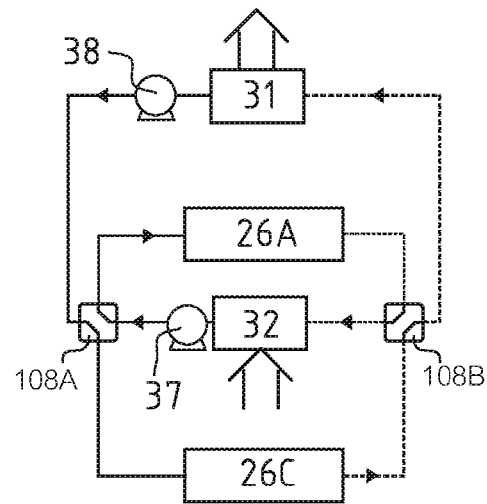
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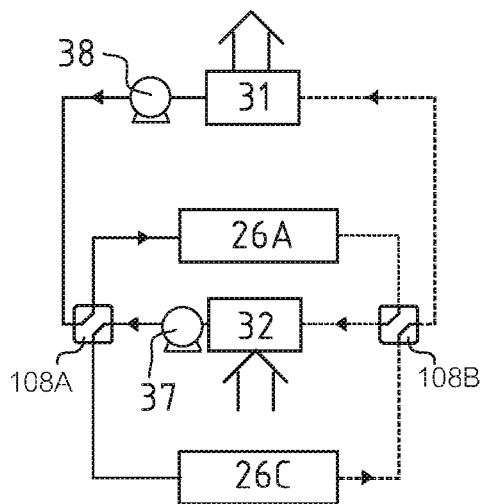
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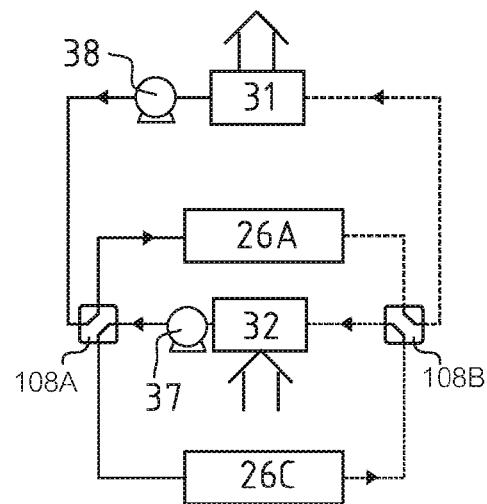
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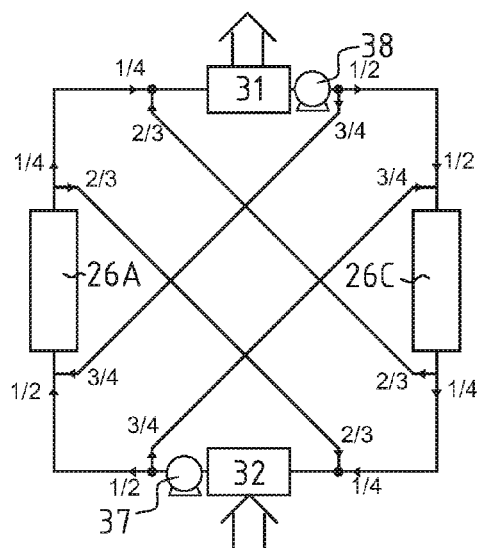
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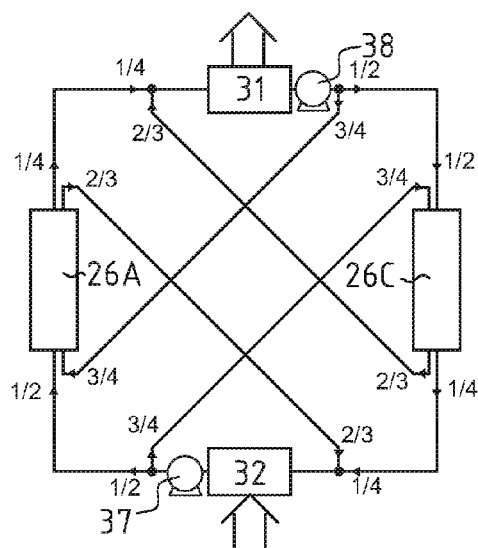
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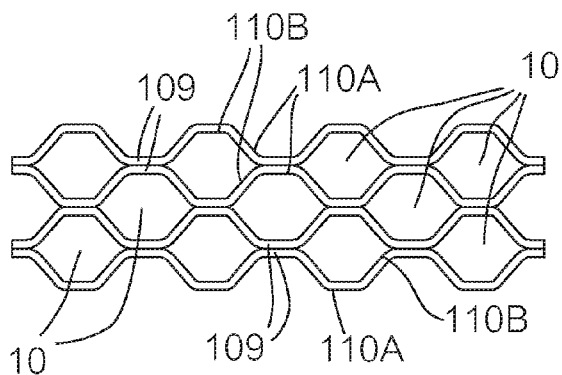
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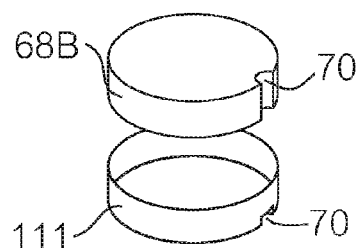
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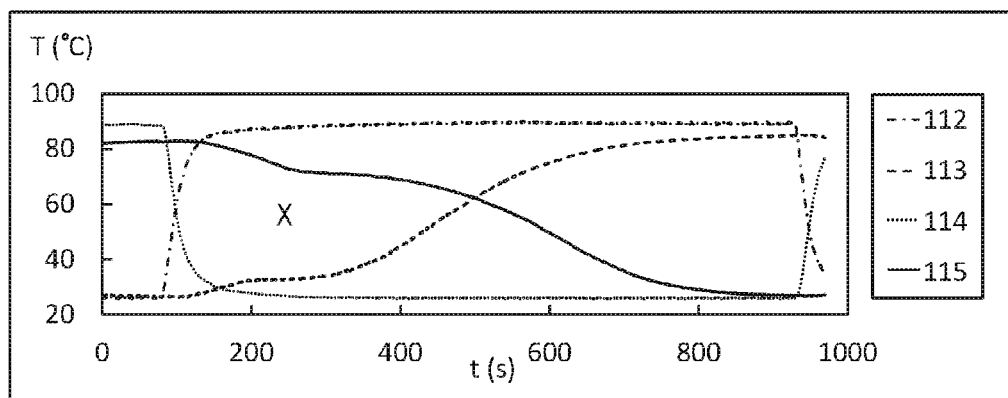
Fig. 36
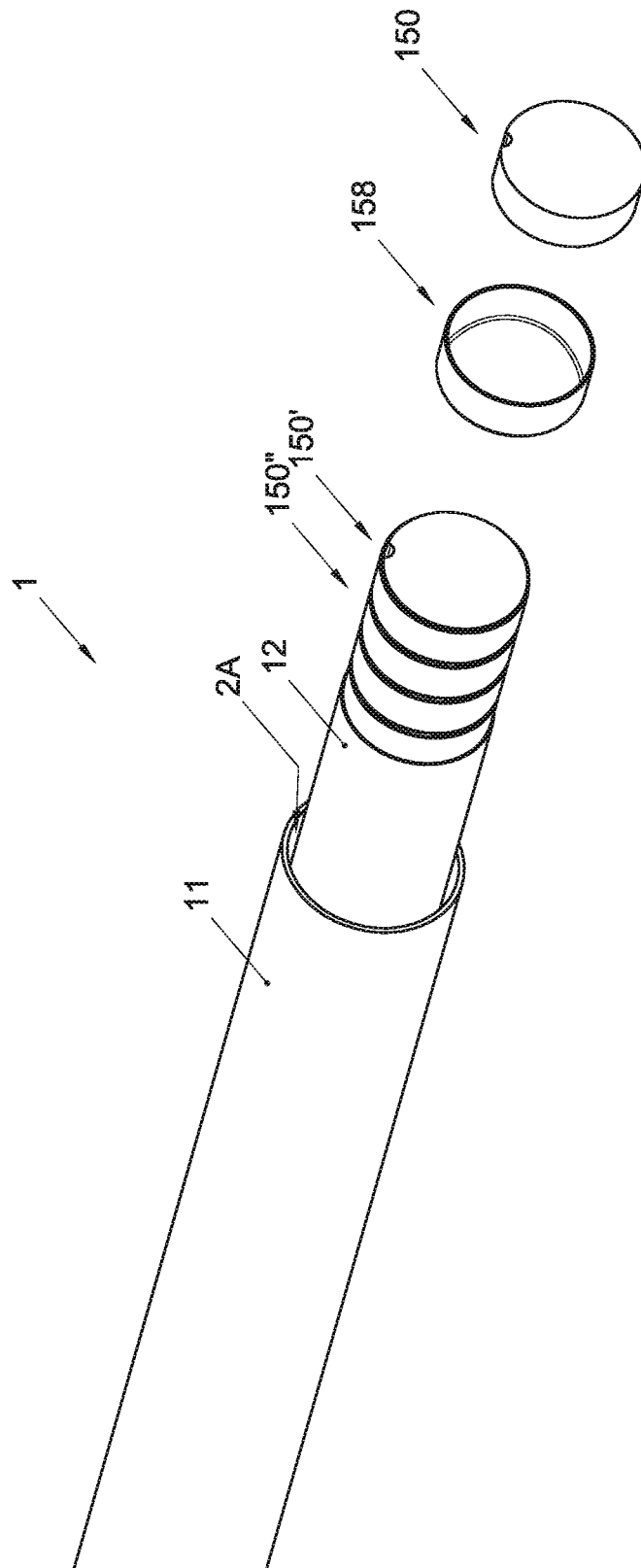
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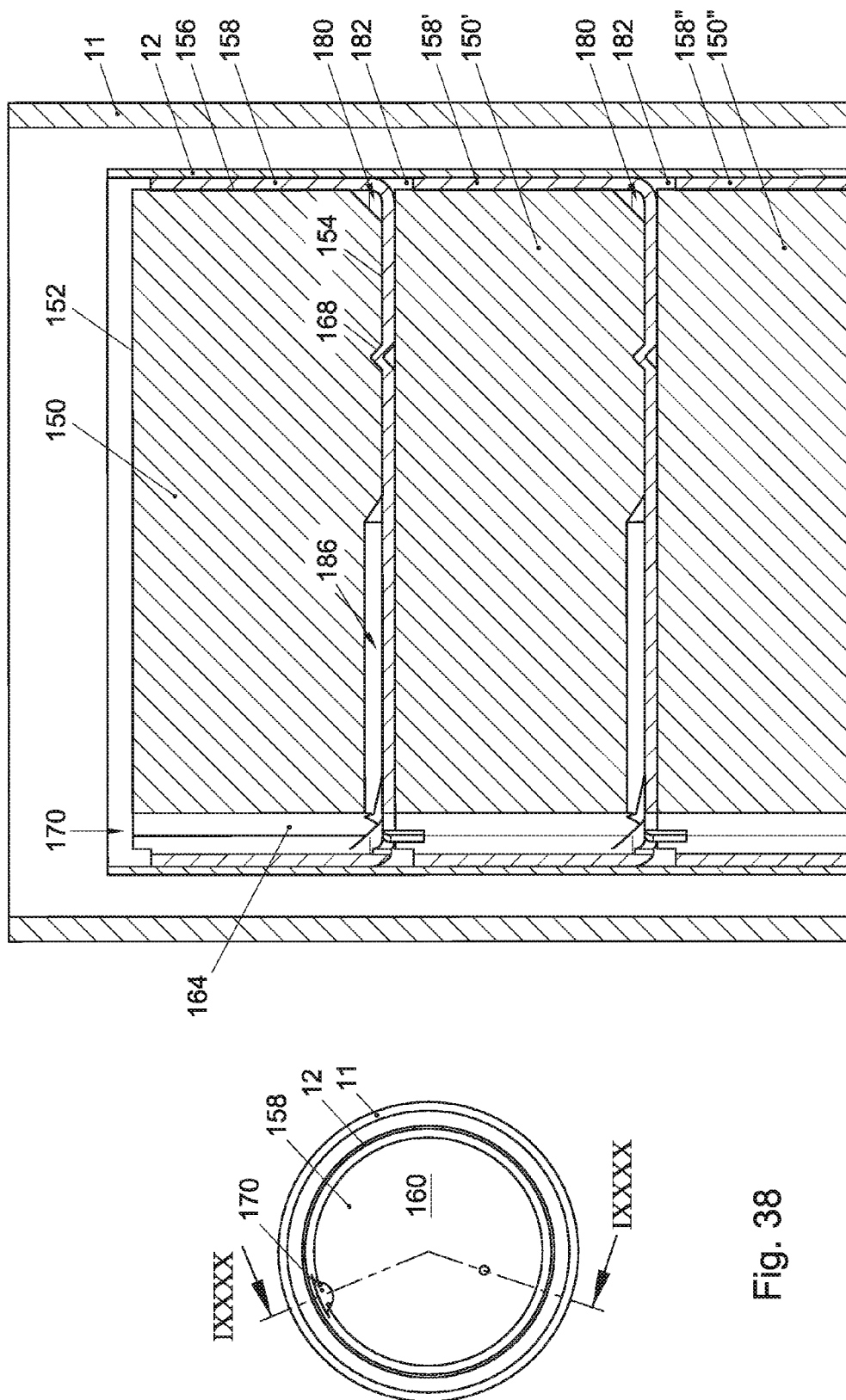
Fig. 39

Fig. 38
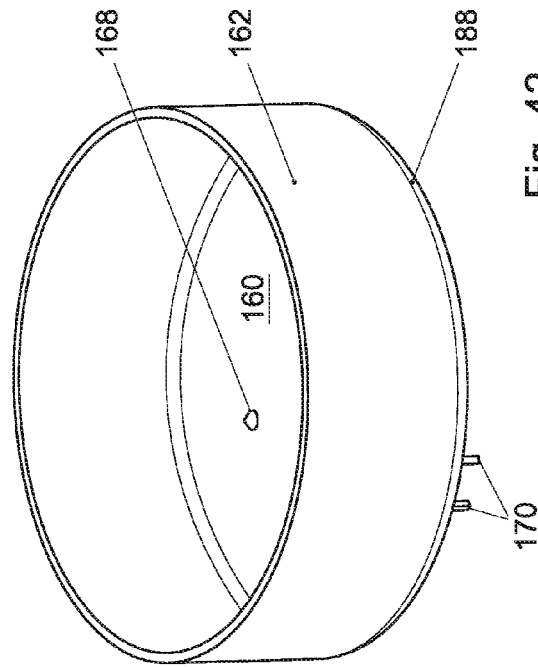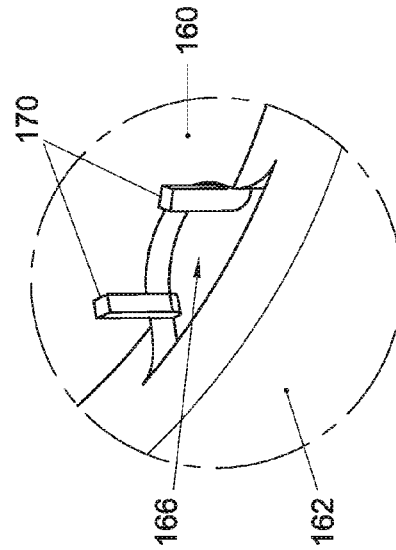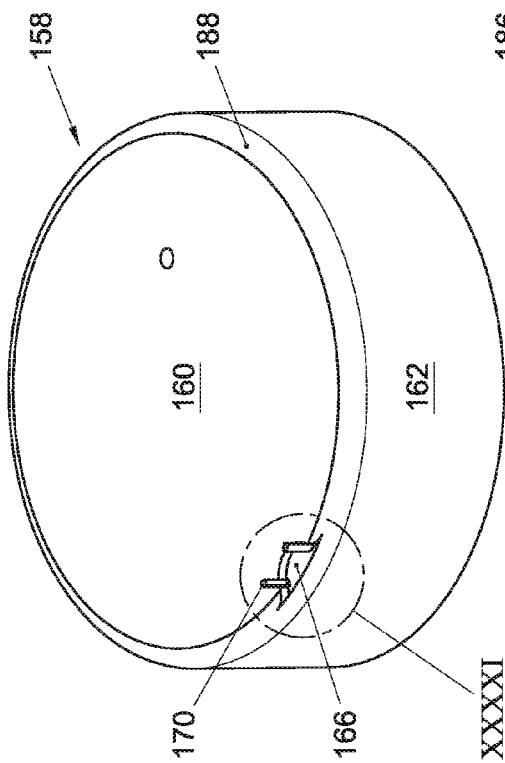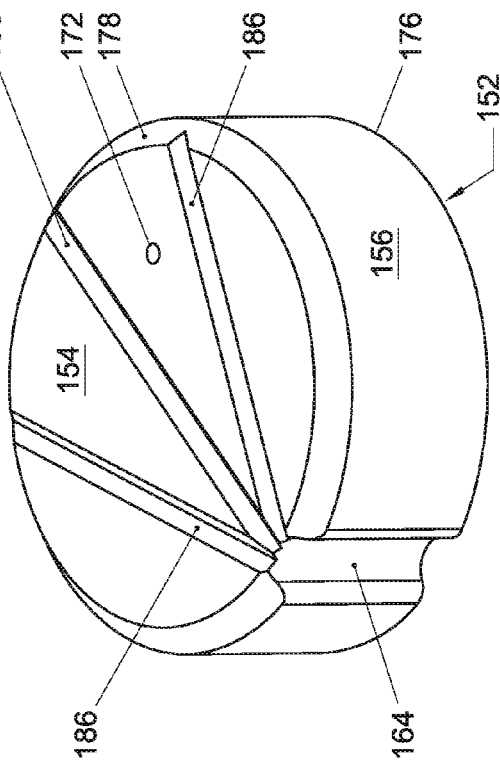
168
162
188

160

170

Fig. 42

170

160

166

162

Fig. 41

158

188

0

160

162

170

166

XXXXI

186

172
178

186

176

154

0

156

152

186

164

Fig. 40

ADSORPTION CELL, ADSORPTION CLUSTER AND ADSORPTION COMPRESSOR AS WELL AS METHOD OF OPERATING AN ADSORPTION COMPRESSOR

PRIORITY APPLICATIONS

This application is a U.S. National Stage Filing under 35 U.S.C. 371 from International Application No. PCT/NL2013/050629, filed on 30 Aug. 2013, and published as WO/2014/035247 on 6 Mar. 2014, which application claims the benefit under 35 U.S.C. 119 to Netherlands Application No. 2009391, filed on 30 Aug. 2012; which applications and publication are incorporated herein by reference in their entirety.

FIELD

The invention relates to an adsorption cell, an adsorption cluster, an adsorption compressor as well as to a method of operation thereof. More specifically, the invention relates to adsorption compressors integrated in a heat pump, in which the compressors make use of a thermal wave through a bed of solid adsorbents.

BACKGROUND

Such compressors are for instance described in U.S. Pat. No. 4,610,148, incorporated herein in its entirety, wherein two beds of adsorbents are used, which are arranged in a shell through which heat exchanging channels are arranged. The heat exchanging channels are connected to a closed circuit of heat exchanging fluid comprising a set of pumps, an additional heat exchanger with cooling action and a heat exchanger with heating action. The shell sides of these adsorbent beds are connected to a heat pump comprising a condenser, an expansion valve and an evaporator. These two beds each are connected both to the condenser and the evaporator side of the heat pump by means of check valves. Further examples of publications that discuss thermal waves in adsorption heat pumps are U.S. Pat. No. 4,637,218; Jones J. A. (Heat recovery systems & CHP 13(1993)363-371); Pons M., Applied thermal engineering, 16(1996)395-404); Sun L. M. et al. (Int. J. Heat mass transfer, 40(1997)281-293); Zheng W. et al. (Heat and mass transfer 31(1995)1-9); Wang, R. Z. (Renewable and sustainable energy reviews 5(2001)1-37); and Critoph, R. E. et al. (Applied Thermal Engineering 24(2004)661-678).

The beds in U.S. Pat. No. 4,610,148 comprise a zeolite, and the applied refrigerant or adsorbing vapor is water. The water vapor originating from the adsorption beds is guided through a set of check valves to a condenser of a heat pump. There the water vapor is condensed in a high pressure condenser, and the condensed water is guided through a pressure release valve, where due to the Joules Thomson effect, the temperature decreases substantially adiabatically, thus providing cooling capacity. In a low pressure evaporator, the water is re-evaporated and can be returned through a set of check valves to that adsorption bed that is cold and accepting the vapor to adsorb. The evaporator provides the actual thermal cooling power of the heat pump.
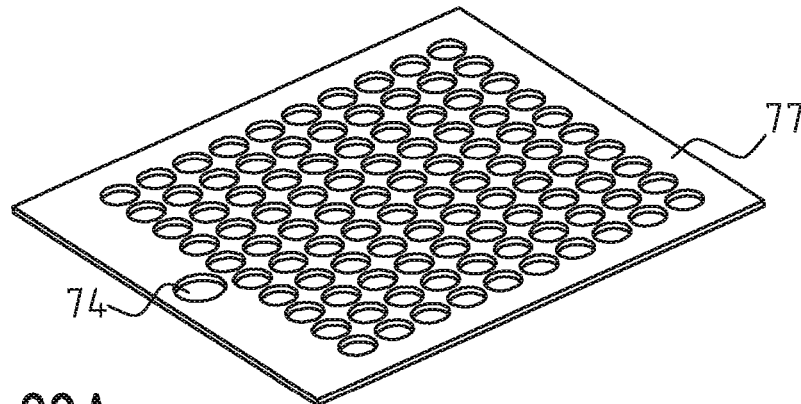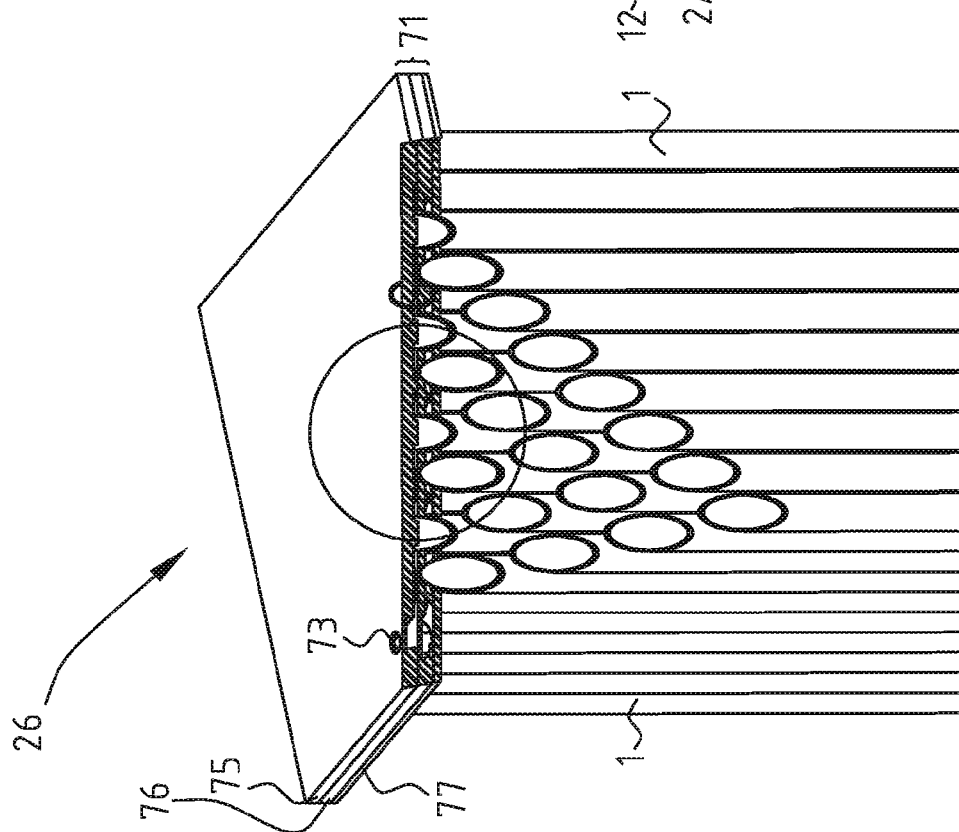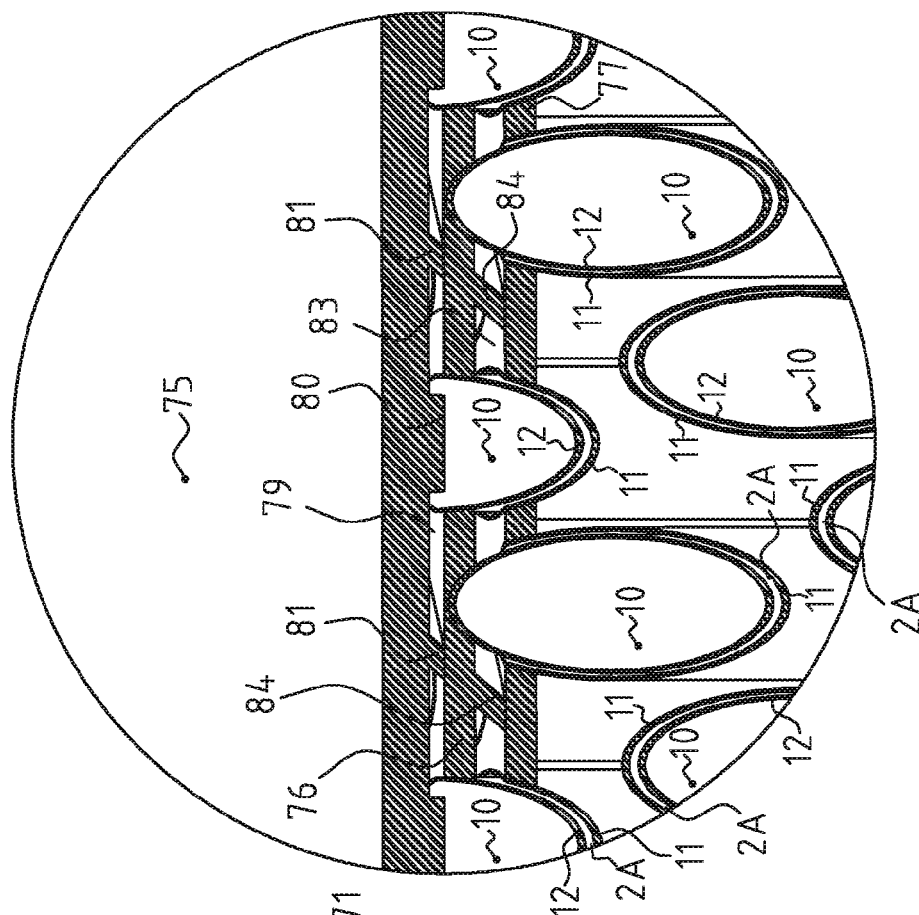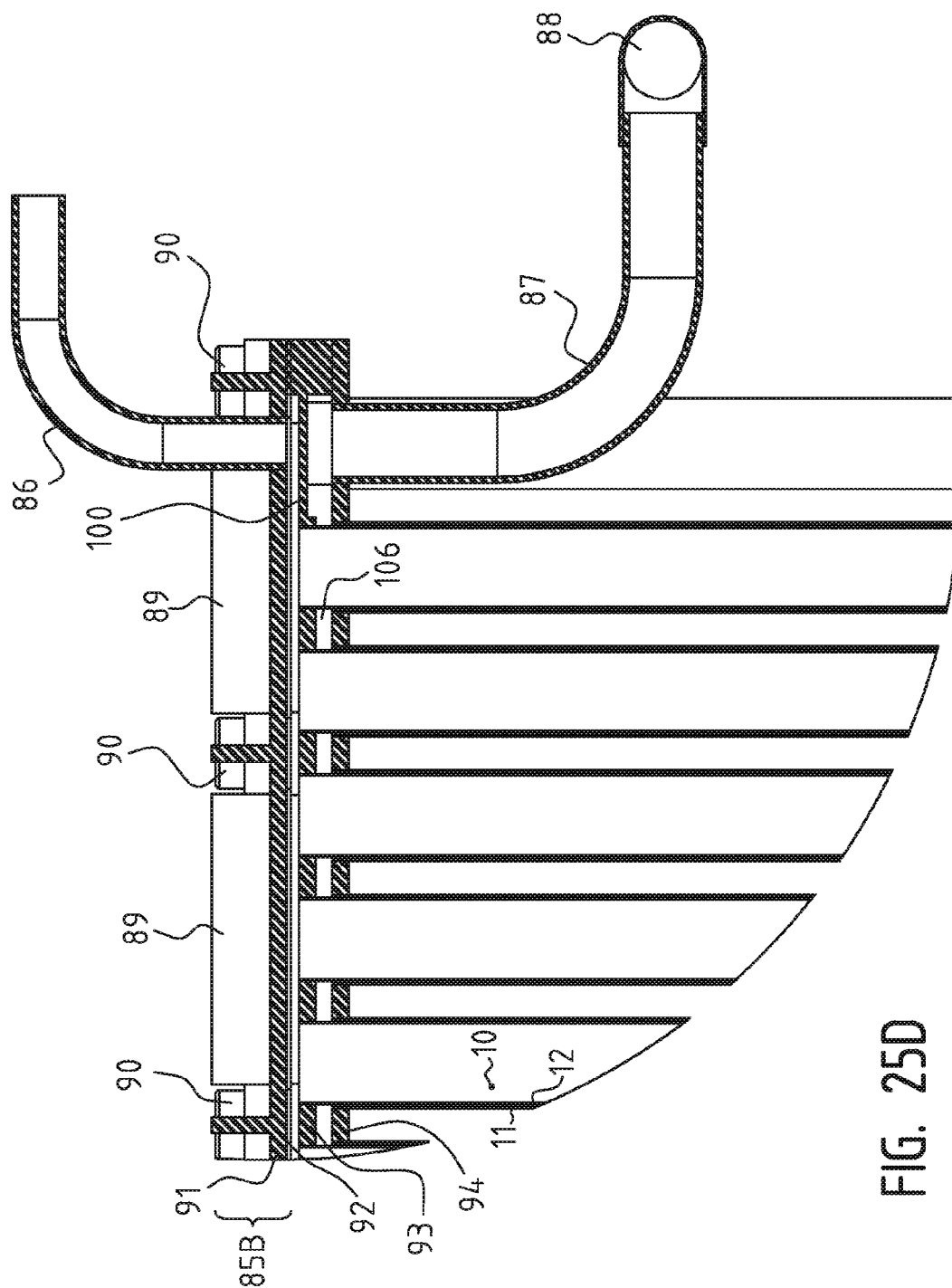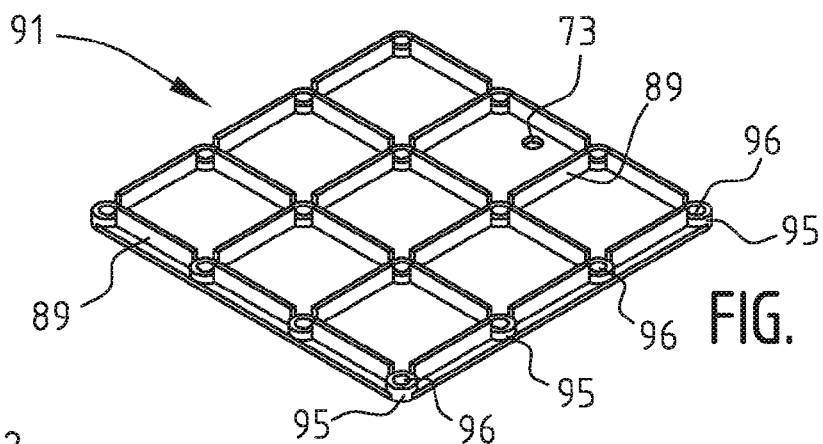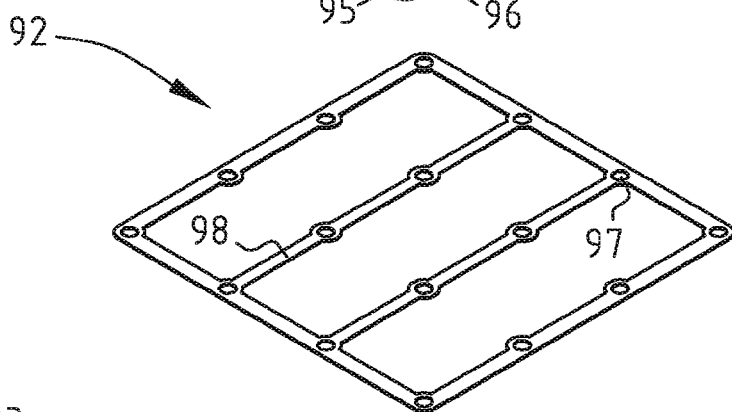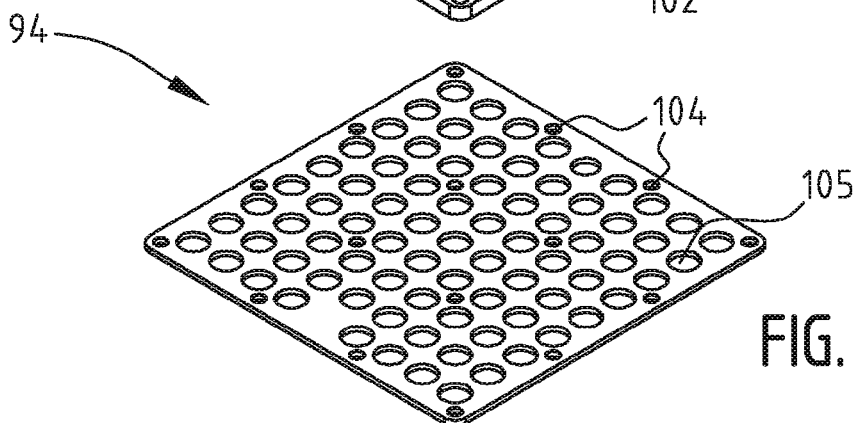
The adsorbing vapor is forced out of the solid adsorption material by heating the material with a heat transfer fluid. In order to have a substantially constant cooling power in the evaporator, two adsorption beds are chosen. One bed is

heated to force out the adsorption vapor while the other is cooled down in order to provide re-adsorption of the adsorption vapor.

A series of check valves allows this alternating operation such that at substantially all times, high pressure vapor is provided to the condenser while relative low pressure vapor is retracted from the evaporator.

In order to increase efficiency in relation to batch cooling and batch heating of the adsorbing material, it was found that heating and cooling the solid adsorbing material by applying a moving temperature profile back and forth through the solid material substantially increased the heat pump performance. This pushing back and forth a temperature profile through the relatively elongated material is known as a thermal wave.

Application of such thermal wave has some further advantages, that only two adsorption cells are needed, a relative simple process flow diagram is needed and a relative uniform refrigerant mass flow over the entire cycle can be provided.

These systems are used because the driving heat can originate from low caloric waste heat or solar heat and the used adsorption vapors or gases can be chosen from non-freon types, which are harmless for the ozone layer.

Disadvantages of these systems are that the condenser, the evaporator and the two adsorbent beds are relative bulky in size. Since water is used as refrigerant, the whole system can only operate at reduced pressures, thus lowering the specific cooling power (SCP) of this system.

An alternative heat pump using zeolite as an adsorbent is presented in U.S. Pat. No. 4,637,218, incorporated herein in its entirety. In this system, again, water is used as a refrigerant medium. In this publication a shell-and-tube arrangement of the adsorption beds and mono block like arrangements of the adsorption bed are proposed. This system, again, suffers from the rather bulky size because of the relative low pressures applied for the evaporation and condensation of the water vapor.

P. Hu et al. (Energy Conversion and Management 50(2009)255-261) describe a refrigeration system comprising an adsorbent bed in an annular container, wherein the heat exchange fluid is on the inside.

A. Sateesh et al. (International Journal of Hydrogen Energy 35(2010)6950-6958) describe a single-stage metal hydride heat pump. This heat pump is based on an absorption process, wherein the metal hydride powder undergoes a chemical change. The term "absorption process" is generally reserved for processes based on chemical absorption, whereas "adsorption process" refers to physical adsorption.

Z. Dehouche et al. (Applied Thermal Engineering 18(1998)457-480) describe the thermal wave concept for a multi-hydride system. This system is also based on chemical changes, rather than physical changes in accordance with the present invention. Dehouche is based on absorption rather than adsorption and discloses a metal foam tube reactor. This type of reactor contains an aluminium foam matrix for improved heat transfer filled with metal hydride powder. The aluminium foam matrix is contained in an inner tube. The heat transfer fluid flows through an annular gap between the inner tube and an outer tube. The use of adsorbent material is not disclosed in Dehouche. To provide this adsorbent material in the form of a stack of pills is also not disclosed nor suggested by Dehouche.

R. E. Critoph et al (Proceedings of the Institution of Mechanical Engineering, 2000, Vol. 214, No. 5, Pages 439-448) relates to a prototype of fast cycle adsorption refrigerator utilizing a novel carbon-aluminium laminate.

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FIG. 4 shows an example of the laminate. The diameter of the stainless steel shell enclosing the laminate is 50 mm. These dimensions are not fit for the adsorption cell that is the object of the present invention, namely an adsorption cell suitable for a thermal wave operated adsorption compressor. Additionally, the heating and cooling of the known laminate is not performed in a heat transfer fluid channel in which a heat transfer fluid flows along the stainless steel shell. Instead, the known laminate is accommodated in a conventional heat pipe and the entire laminate is heated or cooled in batch without a thermal wave being formed in the generator.

WO01/69146 discloses a sorber that includes a plurality of disks of sorbent material such as sintered zeolite or ceramics. The disks are stacked together face-to-face. The disks may have grooves in one or both of its two faces which provide passageways between each adjacent pair of disks. Heating of the sorbent material may be effected by means of an electromagnetic wave generator, more particularly a magnetron or by conventional heaters. For the embodiment with the electromagnetic wave generator it is disclosed to locate between each pair of sorbent disks a electrically conductive disk. The conductive disks are metallic and are electrically coupled to an inner conductor or an outer housing which is also a conductor. More particularly, the successive ones of conductive disks are coupled alternately to either the inner conductor or the outer conductive housing so as to increase the magnitude of the electric field applied across the sorbent disks. WO01/69146 does not disclose that the sorber is intended and suitable for thermal wave operation. In fact, the only type of heating that is disclosed in WO01/69146 is bulk heating.

SUMMARY

Although the known thermal wave based adsorption heat pump systems result in an improvement of efficiency, in particular with respect to coefficient of performance (COP) and specific cooling power (SCP), it is still desirable to improve on COP and SCP.

It is an object of the invention to mitigate or solve the above described and/or other problems of the heat pumps and the adsorption compressors in the art, while maintaining and/or improving the advantages thereof. More specifically, an object of the invention can be to reduce the size of the complete heat pump and the size of the adsorption compressor, to provide more practical bed arrangements and to provide a system and a method that is more economical and efficient in its operation. A further object is to provide a method of operating an adsorption compressor having improved COP and SCP.

These and/or other objects are reached by an adsorption cell suitable for a thermal wave operated adsorption compressor comprising:

an elongated heat transfer fluid (HTF) channel defining a heat transfer fluid flow path having an axis and a length;

at least one solid adsorption material housing extending in the heat transfer fluid channel defining an adsorption material chamber;

solid adsorption material that is accommodated in the solid adsorption material chamber and that is in direct heat transferring contact with heat transfer fluid that, in use, flows through the heat transfer fluid channel, wherein said solid adsorption material comprises a stack of units, each unit comprising:

a pill of adsorption material, each pill including a top, a bottom and at least one side; and

each unit being associated with:

a cup from a heat conductive material, the pill of the unit being at least partly surrounded by the associated cup, each cup including:

a cup bottom wall forming a heat conductive lamella extending between the pill of the unit and a pill of an adjacent unit in the stack of units, parts of the cup bottom wall being in abutting contact with associated parts of the bottom of the pill of the unit and parts of the cup bottom wall being in abutting contact with associated parts of the top of the pill of the adjacent unit; and

a jacket wall of which at least a part is in abutting contact with an inner side of the solid adsorption material housing;

wherein the surface conformity and roughness of the associated parts of the bottom of the pill of the unit and of the associated parts of the top of the pill of the adjacent unit on the one hand and of the abutting parts of the cup bottom wall on the other hand are such that any gap between the abutting parts is less than 30 micron, preferably less than 10 micron.

During operation, the heat to be transferred from the heat transfer fluid to the adsorbing material preferably is as efficient as possible. That is the reason for the provision of the cup that is made from a heat conductive material. The heat conductive material preferably has a heat conduction coefficient that is larger than 100 W/m·K. Examples of such materials are aluminium and copper. For reference it is indicated that the heat conduction coefficient of the adsorption material, which may for example be activated carbon, is typically less than 1 W/m·K. The cup of heat conductive material and the adsorption material have to be in intimate contact to establish a good heat transfer. In view of the fact that both the cup and the pill of adsorption material have a defined shape, gaps may occur between the cup and the pill. These gaps deteriorate the heat conductivity. By virtue of the feature that the surface conformity and roughness of the associated parts of the bottom of the pill of the unit and of the associated parts of the top of the pill of the adjacent unit on the one hand and of the abutting parts of the cup bottom wall on the other hand are such that any gap between the abutting parts is less than 30 micron, preferably less than 10 micron, an excellent heat transfer between the cup and the adsorption material is provided. Indeed, when that feature is met, the heat conductivity resistance within the adsorption material is dominant over the heat conductivity resistance between the cup and the pill.

In an embodiment, a surface conformity and roughness of the part of the jacket wall that is in abutting contact with the inner side of the solid material adsorption housing on the one hand and a surface conformity and roughness of the inner side of the solid material adsorption housing on the other hand are such that any gap between the abutting part of the jacket wall and the inner side of the solid adsorption material housing is less than 30 micron, preferably less than 10 micron. Thus, the heat conductivity resistance between the adsorption material housing and the jacket wall of the cup is minimized and the heat conductivity resistance within the adsorption material plays a more important role than the heat conductivity resistance between the cup and the adsorption material housing.

In an embodiment, the pill has a characteristic dimension r in a plane that is perpendicular to the axis of the heat transfer channel, which characteristic dimension is smaller than 1 cm, preferably smaller than 0.5 cm, more preferably smaller than 0.4 cm.

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With these dimensions, a relatively advantageous combination of SCP and COP may be obtained as will be explained hereafter with reference to FIG. 13.

In order to effectively guide the refrigerant fluid along the stack of units, an embodiment of the cell includes at least one refrigerant channel that extends along the stack of units.

From a point of view of ease of manufacture, an embodiment is provided in which each pill has at least one refrigerant groove in the side, which refrigerant groove extends in the direction of the stack of units, wherein each cup has a hole in the bottom wall or a notch in the jacket wall of which hole or notch the cross sectional area substantially corresponds with the cross sectional area of the refrigerant groove, wherein the refrigerant grooves of the pills are aligned relative to each other and wherein the holes or notches of the cups are aligned relative to the refrigerant grooves so that they together form the at least one refrigerant channel.

A pill with a refrigerant groove in the side is more easy to press than a pill with, for example, a central axial through bore.

The alignment of the refrigerant groove in the side of the pill and the hole or notch of the cup may be effected in an embodiment in the pill and the cup both have a co-operating structural feature that prevent rotation of the pill within the cup and that define the rotational position of the pill within the cup.

Alternatively or additionally, prevention of rotation of the pill within the cup and stable alignment of the refrigerant groove and the hole or notch of the cup may be effected by means of a kind of glue. Good heat transferring properties of the glue is then beneficial for a good efficiency of the adsorption cell.

In an embodiment, the structural feature in the cup may include a dent forming a cup projection, wherein the associated pill includes an associated pill indentation, wherein the refrigerant groove of the pill and the hole or notch in the cup are aligned when the pill indentation accommodates the associated cup projection.

In an alternative embodiment, the structural feature of the cup may include a jacket wall with a non-circular cross section in a plane parallel to the bottom wall, preferably an elliptical cross section, and wherein the structural feature of the pill includes a non-circular cross section in a plane parallel to the bottom or top of the pill, which pill cross section corresponds with the cross section of the jacket wall.

In order to align refrigerant grooves in the sides of the pills relative to each other within the stack of units, an embodiment is provided wherein the cup includes a structural feature that engages a neighboring pill or cup or that engages a co-operating structural feature of the adsorption material housing.

In an embodiment, the structural feature of the cup may include at least one lip adjacent the hole or notch, which lip engages a wall delimiting the refrigerant groove of a neighboring pill or engages a notch, a recess or cut-away in the jacket wall of the neighboring cup.

In an alternative embodiment, the structural feature of the cup may include a jacket wall with a non-circular cross section in a plane parallel to the cup bottom wall, preferably an elliptical cross section, wherein the adsorption material housing includes a non-circular cross section in a plane parallel to the cup bottom wall, which non-circular adsorption material housing cross section corresponds with the cross section of the jacket wall.

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A slightly elliptical cross section still has good resistance against pressure differences between the inside and the outside of the inner shell, just like a circular cross section. These pressure differences occur during the use of the cell.

In order to guide the refrigerant fluid to the adsorption material, it is preferred to have an embodiment in which one or more cross channels are present in said pill that extend substantially perpendicularly to the refrigerant channel and that are in fluid connection with the axial refrigerant channel. In an embodiment the cross channels may be formed by grooves in the top and/or bottom of the pill. Thus, the refrigerant fluid is guided over the bottom and/or top surface of the pill.

To even further improve the distribution of refrigerant fluid over the pill, an embodiment of the adsorption cell may be characterized in that an edge formed by the side of the pill and the bottom and/or the top are rounded or chamfered to form the at least one perimeter channel. Thus one or two peripheral channels may be provided without any additional manufacturing costs. When the pill is manufactured, for example in a pressing operation, the chamfered or rounded edges may be provided simultaneously.

In an embodiment, an edge between the jacket wall and the cup bottom wall may rounded or chamfered. Thus, the jacket wall may have some radial play by deformation in the area of the radius. Thus a very good fit of the cup in the adsorption material housing may be obtained. Such a good fit is important for improving the heat transfer conductivity between the adsorption material housing and the cups with the pills.

An efficient heat transfer and adsorption efficiency within the pill is obtained in an embodiment in which a height of an individual pill defined by the largest distance between the top and the bottom is less than 5 mm, preferably less than 2.5 mm.

In an embodiment, a height of the jacket wall of the cup is less than thickness of the pill which is defined by the greatest distance between the bottom and the top of the pill, so that neighboring cups of the stack of units do not contact each other. This is advantageous for an embodiment in which the direction of the stack is parallel to the flow direction of heat transfer fluid in the HTF channel and helps to create a good thermal wave along the length of the adsorption material.

The invention also provides a cluster comprising a matrix of adsorption cells according to the invention, wherein the HTF channels of the individual adsorption cells are on both distal ends in fluid connection with a HTF manifold and wherein the refrigerant channels of the individual adsorption cells are on one or both distal ends in fluid connection with a refrigerant manifold.

Further, the invention provides an adsorption compressor, suitable for thermal wave operation, comprising:

at least one first cluster according to the invention;

at least one second cluster according to the invention;

a refrigerant circuit including:

a condensor having a condensor inlet and a condensor outlet;

an expansion valve;

an evaporator having an evaporator inlet and an evaporator outlet, the evaporator inlet being connected to condensor outlet via the expansion valve; and

an assembly of refrigerant valves that is configured to alternatively connect the refrigerant manifold of the first cluster and the refrigirant manifold of the second cluster to the inlet of the condensor and the outlet of the evaporator;

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a heat transfer fluid circuit including:

a first heat source having the function of a HTF heater;

a second heat source having the function of a HFT cooler and having a lower temperature than the first heat source;

a HTF valve assembly that is configured to be switched to conduct heat transfer fluid between the HTF manifolds (**20***a-d*, **21***a-d*) of the at least two clusters and the HTF cooler and the HTF heater;

at least one pump for pumping around heat transfer fluid;

an electronic controller configured to control the HTF valve assembly to provide four modes of operation in which the heat transfer fluid can be pumped around:

a first mode wherein a single circuit of heat transfer fluid is arranged through the HTF heater, the first cluster, the HTF cooler, the second cluster and back in the HTF heater;

a second mode comprising two separated shortcut circuits: a first one in which heat transfer fluid flows from the HTF heater to the first cluster and returns to the HTF heater, and a second one in which heat transfer fluid flows from the HTF cooler to the second cluster and returns to the HTF cooler;

a third mode wherein a single circuit of heat transfer fluid is arranged from the HTF heater to the second cluster, to the HTF cooler and via the first cluster back again in the HTF heater; and

a fourth mode comprising two separated shortcut circuits: a first one in which the heat transfer fluid flows from the HTF heater to the second cluster and back in the HTF heater, and a second one in which heat transfer fluid flows from the HTF cooler to the first cluster and returns to the HTF cooler.

Such an adsorption compressor has an improved SCP and COP due to the improved conductivity of heat throughout the adsorption material.

Finally, the invention provides a method of cooling or heating e.g. by using a relative low caloric heat such as a solar boiler or a waste heat stream or a high caloric heat source such as a gas flame, comprising the use of an adsorption cell according to the invention or a cluster according to the invention. In particular the method comprises the following steps to be executed in any suitable order:

a) providing an adsorption compressor according to the invention,

b) heating in a first mode the adsorption material in a first cluster by gently pumping hot heat transfer fluid exiting from a HTF heater in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep decreasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the first cluster, wherein the adsorbed refrigerant is desorbed from adsorption material of the first cluster at relative high pressure, forced through check valve towards condenser, condensed and forced through expansion valve and left to evaporate and perform cooling action in evaporator,

c) cooling during step b) in a first mode the adsorption material in a second cluster by gently pumping cold heat transfer fluid exiting from a HTF cooler in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantial steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the

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elongated adsorption cells within the second cluster, wherein the refrigerant is adsorbed by the adsorption material of the second cluster at relative low pressure, originating from the evaporator through check valve,

d) switching at a predetermined moment, to a second mode, cooling the adsorption material in a first cluster by gently pumping cold heat transfer fluid exiting from a HTF cooler in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the first cluster, wherein the refrigerant is adsorbed by the adsorption material of the first cluster at relative low pressure, originating from the evaporator through check valve,

e) heating during step d) in the second mode the adsorption material in a second cluster by gently pumping hot heat transfer fluid exiting from a heater in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep decreasing heat profile in axial direction, the thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the second cluster, wherein the adsorbed refrigerant is desorbed from adsorption material of the second cluster at relative high pressure, forced through check valve towards condenser, condensed and forced through expansion valve and left to evaporate and perform cooling action in evaporator;

f) switching back in the first mode and repeating steps a-f.

A method of operating an adsorption compressor system in accordance with the present invention preferably uses a system, which comprises a hot source and a cold source and at least a first and a second adsorption bed, wherein the first bed has an initial temperature that is lower than the initial temperature of said second bed, in which system heat is circulated using a heat transfer fluid (HTF), the method comprising the following phases:

phase A) comprising the steps of:

heating the first adsorption bed by feeding HTF to it, coming from said second bed, optionally via said hot source, while maintaining a thermal wave in said first bed; and

cooling the second adsorption bed by feeding HTF to it, coming from said first bed, optionally via said cold source, while maintaining a thermal wave in said second bed; wherein phase A) is maintained until the exit temperature of said first bed and said second bed are essentially the same

and phase B) comprising the steps of:

feeding the HTF effluent of said first bed to said hot source and from said hot source back into said first bed; and

feeding the HTF effluent of said second bed to said cold source and from said cold source back into said second bed; wherein phase B) is maintained until the temperature in said first bed is essentially homogeneous and the temperature in said second bed is also essentially homogeneous and lower than the temperature of said first bed, wherein the flow rates of said HTF through said first and second bed may be higher than in phase A).

In the prior art thermal wave systems, a single HTF loop is used incorporating the two adsorption beds with a heating and cooling device located in between them. A reversible pump or a one-way pump with suitable switching valves is used to reverse the thermal wave through the beds once the

wave approaches one of the ends of the bed. In this way, a complete cycle is divided into two half-cycles. Each half-cycle begins after the flow direction of the heat transfer fluid is reversed. The switching moment of the flow reversal is taken before the thermal wave breaks through, viz. when it reaches the other side of the bed.

Without wishing to be bound by theory, the present inventors believe that in reality, the thermal wave is significantly less steep than originally suggested in the prior art (e.g. in U.S. Pat. No. 4,610,148 and U.S. Pat. No. 4,637,218). This means that the thermal wave has a rather flat temperature profile along the length of the cell so that much of the adsorbed refrigerant towards the end of the cell is not yet ad- or desorbed when the wave reverses, which limits the SCP significantly. One way to improve this would be to allow more refrigerant to be adsorbed or desorbed and higher SCP values can be achieved if the thermal wave is allowed to progress more towards the end of the cell so that more refrigerant can be ad- and desorbed during one half-cycle. However, in this situation the COP deteriorates rapidly due to the progressively increased temperature differences over the heating and cooling devices. Thus there is a trade-off between COP and SCP.

The present invention provides a new thermal wave cycle which improves the SCP while maintaining a high COP.

The invention can be illustrated while referring to FIG. 29A-D. For simplicity in this figure only the flow direction of HTF is indicated, while the refrigerant fluid connections and flows are not drawn. It is to be understood that the refrigerant fluid connections may be located at either side of the beds, or even at both sides of the bed. In this last situation, one side can be connected via a check valve to the refrigerant high pressure line and the other side can be connected via a check valve to the refrigerant low pressure line.

The refrigerant can in principle be any substance known in the art for this purpose. Preferably the refrigerant is selected from ammonia, water (steam), carbon dioxide, methanol, n-butane and the like. Most preferred is ammonia, in particular in combination with active carbon as adsorption material.

The adsorbent can in principle be any substance known in the art for this purpose. Preferably it is selected from active carbon, zeolites, metal organic frameworks, $BaCl_2$ and the like.

The entire adsorption and desorption cycle may be split into four (instead of two) phases, of which phases A and C are heat regenerating phases and phases B and D are non heat regenerating phases. The adsorption beds in the system need to be suitable for a thermal wave operated adsorption compressor.

In phase A, bed 1 is heated by high-temperature HTF from the hot source. Because of the thermal wave operation, initially low-temperature HTF exits bed 1, after which this HTF is further cooled by the cold source. At the same time, bed 2 is cooled by this low-temperature HTF from the cold source. Again because of the thermal wave operation, initially high-temperature HTF exits bed 2, after which this HTF is further heated by the hot source.

At a certain point phase 2 is started, basically when the two temperatures of the HTF exiting bed 1 and 2 are essentially equal to each other. These exit temperatures are considered essentially the same when the absolute temperature difference between the exit temperatures is less than 40%, preferably less than 30%, more preferably less than 20%, even more preferably less than 10%, typically from 0-5%, of the temperature difference between the hot and

cold sources. A HTF switching system can be used to connect bed 1 directly to the hot source and bed 2 directly to the cold source to finalize the thermal wave in the beds without heat regeneration, until the temperatures of the beds are essentially uniform.

In phase A heat is regenerated between both beds. In the example depicted in FIG. 28 the maximum quantity of heat that can be regenerated is (under the assumption of a constant HTF flow in time) proportional to area X. This maximum quantity of heat is reached when the exit temperatures of the first bed and the second bed are essentially the same as defined above.

In phase B, the bed temperatures are considered essentially homogeneous when the absolute difference between the entrance and exit temperatures is less than 30%, preferably less than 20%, more preferably less than 10%, even more preferably less than 5% of the temperature difference between the hot and cold source.

FIGS. 12 and 28 show examples of the exit temperatures of bed 1 and bed 2 during the phases A and B. The shaded area A is proportional to the heat that needs to be supplied by the heater to the HTF during the heat regenerating phase, and the shaded area B is proportional to the heat that needs to be supplied during the non regenerating phase.

At the end of phase B, the first bed that was firs cold is now the hotter bed, while the second bed that was first hot is now the cooler bed. The operation can be repeated as described above, but now with the roles of the two beds interchanged.

For example, next, a new heat regenerating phase may be started in phase C. Operation is similar to phase A but the role of beds 1 and 2 is reversed: bed 1 is cooling and bed 2 is heating. This is followed by phase D, which is another non-regenerative phase with the role of beds 1 and 2 reversed.

The direction of the thermal wave in the beds may be the same for all phases and this is preferred. Alternatively, after phases A and B the HTF flow direction and thermal wave direction can be reversed in phases C and D, as depicted schematically in FIG. 30. This requires, however, a different and more complicated HTF fluidic switching system.

Many modifications and alterations are possible based on the above-described principle, as will become clear in the following.

For instance, the switching between phases may be carried out by using switching valves, in particular three-way valves. Alternatively separate lines with two-way valves can be used, as is depicted in FIGS. 32A-D. Four-way valves may also be used, see FIGS. 33A-D.

One of the additional advantages may be that the pumps only have to operate in a one-way direction, which allows the use of standard components and engineering practices.

In a preferred embodiment of the invention an adsorption cell is provided suitable for a thermal wave operated adsorption compressor comprising an elongated solid adsorption material; an elongated heat transfer fluid channel in direct heat transferring contact with the solid adsorption material, wherein the characteristic dimension r of the adsorption material is chosen such that the relation:

$$\frac{r^2}{\lambda_{eff}} < \frac{\gamma}{SCP}$$

is fulfilled, wherein λ_{eff} is the effective thermal conductivity, γ is a design parameter and SCP is the specific cooling

power, wherein $\gamma < 0.0025$ K·m³/kg, wherein SCP>250 W/kg and wherein $0.5 < \lambda_{eff} < 20$ W/mK. The characteristic dimension r may be taken as the radius of the adsorption material in case the adsorption cell has a circular cross-section. In case the cross-section is non-circular (e.g. polygonic or elliptical), r is the equivalent radius, viz. the radius of a circle having the same surface area as the non-circular cross-section in question.

The characteristic dimension of the heat transfer fluid channel d_{HTF} can be chosen such that the relation:

$$Biot = \frac{Nu}{8} \frac{\lambda_{HTF}}{\lambda_{eff}} \frac{r}{d_{HTF}} > 1$$

is fulfilled, wherein Biot is Biot Number, λ_{HTF} is the effective thermal conductivity of the heat transfer fluid, Nu is Nusselt Number, d_{HTF} is the characteristic dimension of the heat transfer channel, wherein $0.1 < \lambda_{HTF} < 10$ W/m·K, Biot Number>1 and wherein $4 < Nu < 6$.

By these specific dimensions an efficient operation can be obtained, as is explained in further detail herein below.

The characteristic dimension of the heat transfer fluid channel can be less than 1 mm and the characteristic dimension of the adsorption material is preferably less than 1 cm. The adsorption material can be arranged in a inner cylindrical wall, provided with an axial refrigerant channel. The heat transfer fluid channel can be an annular heat transfer fluid channel, coaxially arranged around the adsorption material between the inner (cylindrical) wall and an outer (cylindrical) wall.

The invention further relates to a cluster comprising a matrix of adsorption cells as described herein above, wherein the annual heat transfer fluid channels of the individual adsorption cells are in fluid connection on both distal ends with a heat transfer fluid header, which is a manifold that can collect or distribute the heat transfer fluid and wherein the axial refrigerant channels of the individual adsorption cells are in fluid connection on one or both distal ends with a refrigerant header, which is also a manifold and that can collect or distribute the refrigerant.

The heat transfer fluid channel of an adsorption cell can be provided with a radial conductor, e.g. a corrugated plate.

The adsorption material and/or the refrigerant channel of each of the cells or clusters can be through a set of check valves in fluid contact with a refrigerant loop, which can comprise a condenser, an evaporator and an expansion valve configured in such a way that the refrigerant is allowed in and out of the adsorption material of the cells or clusters and is allowed to be conducted in one direction only through the refrigerant loop.

The separate cells or clusters can be interconnected by a pressure equalizing conduit comprising a valve. The refrigerant loop can further be in fluid connection with an auxiliary container, comprising an adsorption mass and a temperature controllable heater.

The herein described method can have a cycle time complies with the equation:

$$t_{cycle} = \frac{\Delta x_{net} \cdot \Delta h}{SCP}$$

wherein t_{cycle} is the total cycle time of a sorption cell or cluster i.e. the total cycle time for the ad- and desorption mode, Δh is the enthalpy change [J/g] of the refrigerant gas

that is providing the cooling power and Δx_{net} is the net amount of gas that is ad- and desorbed from the adsorption material, such as carbon in one ad- and desorption cycle, expressed in gram gas per gram adsorption material.

The performance of these heat pumps is in general caught in two parameters, firstly the coefficient of performance (COP) and secondly the specific cooling power (SCP). The coefficient of performance is the ratio between the thermal cooling power $P_{cooling}$ and the thermal input power P_{in}.

$$COP = \frac{P_{cooling}}{P_{in}} \tag{1}$$

The specific cooling power is the thermal cooling power divided by the mass ($m_{adsorber}$) of the adsorber.

$$SCP = \frac{P_{cooling}}{m_{adsorber}} \tag{2}$$

In the heat pump according to the invention, the used adsorption material can be e.g. solid amorphous carbon containing material, and the refrigerant or adsorbing gas can be NH_3. With this specific combination of adsorbing material and adsorbing gas, a high SCP can be achieved, leading to a relative compact and light compressor.

Further advantages of such heat pump is a relative high COP and relative high thermodynamic efficiency, a relative high temperature flexibility without compromising on SCP and COP, a relative constant production of cold or heat, fast start up and stop times of typically in the minutes range and relative moderate costs.

A further aspect of the invention is a cell for an adsorption compressor, wherein the cell is comprising adsorption material and at least one separate heat transfer fluid channel in heat transfer contact with the outside of the adsorption material, wherein the relative dimensions of the diameter or height of the heat transfer channel, i.e. the characteristic dimension of the heat transfer fluid channel in relation to the height or the characteristic dimension of the adsorption material and its material properties is dictated by the Biot number, wherein the Biot number is more than or equal to 1.

The Biot number represents herein the ratio of the heat resistance in the adsorption material and the heat resistance in the heat transfer fluid, as is presented in equation 3.

The heat resistance of the adsorption material can be deduced from geometric and material properties, the heat resistance in the heat transfer fluid can be deduced from the geometric aspects of the heat transfer fluid channel and the relevant Nusselt relation for the dominant flow regime inside the heat transfer fluid channel. In effect the lower the value of Biot below unity, the more of the radial heat difference is found within the heat transfer fluid, instead of within the adsorption material which will ultimately lead to an unwanted more flattened (dispersed) thermal wave for the given characteristic dimension (e.g. radius) and heat conductivity of the adsorption material. Accordingly, the Biot number should be larger than one for efficient operation. For a concentric heat transfer fluid jacket around an elongated circular tube containing adsorption material the relevant Biot relation can be represented by:

$$Biot = \frac{R_{inside}}{R_{surface}} = \frac{R_{inside}}{R_{HTF}} = \frac{\frac{1}{\lambda_{ads}} \frac{r}{2}}{\frac{1}{\lambda_{HTF}} \frac{4d_{HTF}}{Nu}} = \frac{Nu}{8} \frac{\lambda_{HTF}}{\lambda_{ads}} \frac{r}{d_{HTF}} \qquad (3)$$

Wherein R_{inside} and $R_{surface}$ are the thermal resistances of the adsorbents and the heat transfer fluid channel respectively. In order to increase the Biot number and thus to steepen the thermal wave for a given characteristic dimension (e.g. radius, r) of the adsorption material and a given effective thermal conductivity of the adsorption material (λ_{ads}), a series of design aspects can be considered: decreasing the characteristic dimension e.g. the thickness (d_{HTF}) of the heat transfer fluid channel, or increasing the effective thermal conductivity of the heat transfer fluid (λ_{HTF}).

The Nusselt number in this relation is approximately 5, for laminar flow. Since turbulent flow is preferably to be avoided in order to keep the pressure drop low, this number is preferably not changed.

When the heat transfer fluid is water, the λ_{HTF} is approximately 0.6 W/mK, when the adsorption material is commercially available amorphous carbon the λ_{ads} is approximately 0.8 W/mK and when the characteristic dimension (e.g. radius) of the adsorption material is chosen to be 0.5 cm, the diameter of the heat transfer channel should be less than 1 mm, or less than approximately one fifth of the characteristic dimension (e.g. radius) of the adsorption material.

Concluding, for a proper efficient operation of the adsorption compressor, the dimensional relation between the diameter or height of the heat transfer channel and the characteristic dimension (e.g. radius) or height of the adsorption material should obey:

$$\frac{r}{d_{HTF}} > \frac{8}{Nu} \frac{\lambda_{ads}}{\lambda_{HTF}} \qquad (4)$$

From this it follows that the heat transfer fluid channel should be small. On the other hand, the diameter or the height of the heat transfer fluid channel can not be chosen too small, because of efficiency losses due to increased hydraulic pressure drop over the length of the fluid transfer channel. The pressure drop Δp over an annular elongated channel for laminar flow is given by:

$$\Delta p = \dot{m} \cdot 6 \cdot \frac{\mu_{HTF}}{\rho_{HTF}} \cdot \frac{l}{\pi r d_{HTF}^3} \qquad (5)$$

Wherein $\dot{m}$ is the mass flow of heat transfer fluid through the annular channel, μ_{HTF} is the dynamic viscosity of the heat transfer fluid, ρ_{HTF} is the density of the heat transfer fluid, r is the inner (equivalent) radius of the annular channel and d_{HTF} is the thickness of the annular channel, i.e. in case of an annular HTF channel, the difference between the inner and the outer radius of the annular HTF channel.

The mass flow through the channel is dictated by the thermal power needed in the cell $P_{in,HTF}$, the cycle time based average temperature difference between the temperature of the heat transfer fluid exiting the heater and the temperature of the heat transfer fluid entering the heater or the difference in temperature over the cooler ΔT.

$$\dot{m} = \frac{P_{in,HTF}}{c_{p,HTF} \Delta T} \qquad (6)$$

The thermal power needed, can be represented as the actual thermal cooling power $P_{cooling}$ divided by the COP.

$$P_{in} = \frac{P_{cooling}}{COP} \qquad (7)$$

wherein the cooling power actually is the specific cooling power times the mass of the adsorption material within the cell m_{cell}, see equation 2, which on its turn can be rewritten as a density ρ_{ads} times the volume of the adsorption material.

$$P_{cooling} = SCP \cdot m_{cell} = SCP \cdot \rho_{ads} \pi r^2 l \qquad (8)$$

By combining the equations 6-8 with equation 5, the pressure drop can be expressed in only design parameters and specific properties of the heat transfer fluid in question.

$$\Delta p = 12 \cdot \frac{SCP}{COP \cdot c_{p,HTF} \cdot \Delta T} \cdot \rho_{ads} \cdot \frac{\mu_{HTF}}{\rho_{HTF}} \cdot \frac{r \cdot l^2}{d_{HTF}^3} \qquad (9)$$

In order not to loose too much efficiency in pressure drop, this should typically not be more than approximately 1 bar when the heat transfer fluid is water. In case thermal oils are used, it should not exceed a few bars pressure.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to further elucidate the invention, exemplary embodiments will be described with reference to the drawings. In the drawings:

FIG. **1** represents a schematic cross sectional side view of an adsorption cell according to a first embodiment of the invention;

FIG. **2** represents a cut out detail of the cross sectional side view of FIG. **1**;

FIG. **3** represents a schematic perspective view of a cell cluster according to a further embodiment of the invention;

FIG. **4** represents a schematic perspective view of a spider connector according to a further embodiment of the invention;

FIG. **5** represents a schematic side view of a cluster according to FIG. **3**;

FIG. **6** represents a schematic perspective view of a cluster of adsorption cells with connection headers or manifolds according to a further embodiment of the invention;

FIG. **7** represents a schematic process flow diagram of the heat transfer fluid flows in a compressor according to a further embodiment of the invention in a first mode of operation;

FIG. **8** represents the flow diagram of FIG. **7** in a second mode of operation;

FIG. **9** represents a schematic process flow diagram of a heat pump comprising an adsorption compressor according to an embodiment of the invention;

FIG. **10**A-I represent a schematic process flow diagram of the heat transfer fluid flow in a further alternative embodiment of the invention;

FIG. **11**A-D represent a schematic process flow diagram of the heat transfer fluid flow in a further alternative embodiment of the invention;

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FIG. 12 represents a schematic temperature profile at the exits of two adsorption bed clusters according to the invention;

FIG. 13 represents a typical relation between COP and SCP according to the invention;

FIG. 14 represents a combined graph depicting equations 3 and 9 in a combined plot according to the invention;

FIG. 15 represents a cross sectional view of an alternative embodiment of a heat fluid channel according to the invention;

FIG. 16 represents a cross sectional view of a further alternative embodiment of the geometry of the adsorption material and the heat transfer fluid channels according to the invention;

FIG. 17 represents a cross sectional view of a further alternative embodiment of the geometry of the adsorption material and the heat transfer fluid channels according to the invention;

FIG. 18A represents a schematic perspective view of a further alternative embodiment of the geometry of the adsorption material and the heat transfer fluid channels according to the invention;

FIG. 18B represents a schematic perspective view of an embodiment of the adsorption material according to the invention;

FIG. 19 represent a schematic view of an alternative embodiment of the refrigerant flow diagram according to the invention;

FIG. 20 represents a schematic perspective view of an alternative embodiment of an adsorption cell cluster according to the invention;

FIG. 21A represents a schematic top view of the cluster according to FIG. 20;

FIG. 21B represents a schematic side view of the cluster according to FIG. 20;

FIG. 21C represents a schematic front view of the cluster according to FIG. 20;

FIG. 21D represents a schematic cross sectional view through line A-A of the cluster according to FIG. 20;

FIG. 21E represents a schematic detailed cut out view of FIG. 21D;

FIG. 21F represents a schematic detailed cut out view of FIG. 21;

FIG. 22A-C represent a schematic perspective exploded view of a distribution element of FIG. 21F;

FIG. 23A represent a schematic perspective partly cut open view of the cluster according to FIG. 20;

FIG. 23B represents a schematic perspective detailed view of FIG. 23A;

FIG. 24 represents a further alternative embodiment of an adsorption cell cluster according to the invention;

FIG. 25A represents a schematic top view of the cluster according to FIG. 24;

FIG. 25B represents a schematic front view of the cluster according to FIG. 24;

FIG. 25C represents a schematic cross sectional view through line A-A of the cluster according to FIG. 25B;

FIG. 25D represents a schematic detailed cut out view of FIG. 25C;

FIG. 26A-D represent a schematic perspective exploded view of a distribution element of the cluster according to FIG. 24;

FIG. 27A represents a schematic perspective cut open view of the cluster according to FIG. 24;

FIG. 27B represents a schematic detailed cut out view of the cluster of FIG. 27A;

FIG. 28 represents a schematic temperature profile at the exits of two adsorption bed clusters according to the invention;

FIG. 29A-29D are illustrations of the principles underlying the method of the present invention showing a schematic process flow diagram of the heat transfer fluid flow;

FIG. 30 represents a schematic process flow diagram of the heat transfer fluid flow;

FIG. 31A-B represent a schematic process flow diagram of the heat transfer fluid flow in a further alternative embodiment of the invention;

FIG. 32A-D represent a schematic process flow diagram of the heat transfer fluid flow in a further alternative embodiment of the invention.

FIG. 33A-D represent a schematic process flow diagram of the heat transfer fluid flow in a further alternative embodiment of the invention;

FIG. 34 represents a cross sectional view of a further alternative embodiment of the geometry of the adsorption material and the heat transfer fluid channels according to the invention;

FIG. 35 represents a schematic perspective view of an embodiment of the adsorption material according to the invention;

FIG. 36 represents the measured temperature profile at the inlets and outlets of two adsorption bed clusters according to the invention;

FIG. 37 represents an exploded view of an example of an embodiment of an adsorption cell including pills and cups;

FIG. 38 is a bottom view of the adsorption cell of FIG. 37;

FIG. 39 is a cross sectional view of the upper part of the adsorption cell over line IXXXX-IXXXX from FIG. 38;

FIG. 40 is an exploded view of an example of an embodiment of a unit including a pill and a cup;

FIG. 41 is detail XXXX from FIG. 40; and

FIG. 42 is an perspective view of the cup of FIG. 40 viewed from a different angle.

DETAILED DESCRIPTION

The expression "effective thermal conductivity" used herein is to be understood as, though not to be considered limited to the thermal conductivity [W/mK] in the dominant heat transfer direction. E.g. for the adsorbents, this is in the coaxially arranged tube design, the conductivity in the radial direction. This thermal conductivity can be enhanced by heat conducting platelets as is proposed in FIG. 18.

In the heat transfer fluid, similar to the coaxial tube design, this is the thermal conductivity in the radial sense. When a corrugated conductive material is placed within the heat transfer fluid channel, the dominant heat transfer direction will be in a tangentially sense, i.e. substantially perpendicular to the meanders of the corrugated plate.

The expression "characteristic dimension" used herein is to be understood as, though not to be considered limited to the relevant height, width, diameter, (equivalent) radius or thickness [m] of the adsorption material or of the fluid transfer channel taken in the direction of the dominant heat transfer. E.g. in the coaxial tube design, the characteristic dimension of the adsorption material is its (equivalent) radius, the characteristic dimension of the heat transfer channel is its width or height. In the case of a stacked plate design, wherein plates of adsorbents are sandwiched between heat transfer fluid channels, the characteristic dimension is half the height of the adsorbents material, since heat transfer occurs substantially symmetrically to both surfaces of the adsorption material layer. In that case this

also applies for the heat transfer fluid channel, wherein the characteristic dimension is half the height of the heat transfer fluid channel.

Yet again in the heat transfer fluid channel, in which a corrugated conductive element is applied, as is shown in FIG. **15**, the characteristic dimension is half the width between two succeeding meanders of the corrugated conductive element.

The expression "specific cooling power" used herein is to be understood as, though not to be considered limited to the thermal cooling power divided by the mass of the adsorption compressor [W/kg]

The quantity "γ" used herein can be understood as, though is not to be considered limited to a design parameter reflecting the maximum temperature difference within the thermal wave in the direction of the dominant heat transfer over the adsorption material divided by the density of the adsorption material. The quantity "γ" is defined as presented in equation 10 herein below.

The expression "base side of a three way valve" used herein can be understood as, though is not to be considered limited to a connection side of a three way valve, which can, by switching the valve, be connected with either a first or a second switching side of the three way valve, such that either a fluid connection is obtained between the base side and on of the two switching sides. The expression elongated used in this specification and in the claims is to be understood as, though not to be considered limited to an property of a physical entity of which one dimension, e.g. measurement or size in a first dimension is far greater than the measurement or size in the other two dimensions. In general at least one dimension departing by at least a factor 2 from the other two could for instance be recognised as being elongated.

The figures represent exemplary embodiments of the invention and should not be considered limiting the invention in any way or form. Throughout the description and the figures the same or corresponding reference numbers are used for the same or corresponding elements.

In FIG. **1** a schematic cross sectional side view of an adsorption cell according to the invention is depicted. In this adsorption cell, which can be seen in FIG. **2** in more detail, a first heat transfer fluid connector **2** and a second heat transfer fluid connector **3** are in fluid connection with a annular heat transfer fluid channel **2a** by means of caps **5**. The cap **5** is provided with a first connector **6** for connection to the heat transfer fluid connection conduit and a skirt **7** for connecting the cap on the cylindrical wall **11**. The cylindrical wall **11** forms the outer shell of the adsorption cell and the outer shell of the heat transfer fluid channel **2a**. In the tubular outer shell **11**, a inner shell **12** is coaxially arranged. This inner shell forms the inner tubular wall of the heat transfer channel **2a**. Inside the inner tubular wall **12** a bed of solid adsorption material **10** is arranged. The inner tubular wall **12** is kept by the caps **8** of which one is provided with a vapor connector **4**. The annular heat transfer channel **2a** is chosen to be of small dimensions, wherein the cap space between the outer and the inner tubular wall is in the range of 1 mm or less. The inner diameter of the inner wall **12** with the solid adsorption material can be chosen to be less than 2 cm, like e.g. less than approximately 1.5 cm. Inside the adsorption material, a vapor passage channel can be arranged. This channel can be coaxially arranged with the outer and inner tubular walls **11** and **12** respectively.

In order to position the inner wall **12** precisely, the annular channel **2a** can be provided with spacers. These spacers can

for instance be obtained by well defined impressions in the outer tubular shell **11**, forming studs that hold the inner tubular wall in position.

FIG. **3** depicts a cluster of adsorption cells as described and shown in FIGS. **1** and **2**. In the embodiment of FIG. **3**, eight cells are arranged in a cluster, wherein the heat transfer fluid connectors are connected to a distribution connector **15**, which can be a spider shaped connector with symmetrical legs, which on its turn is connected to a T-connector **16**. The vapor conduits **4** are at one side connected to the adsorption material inside the inner cylindrical wall **12** of the adsorption cells **1** and at the other side to the vapor conduit connectors **17**, connecting the vapor conduits **4** through a set of check valves to either the evaporator or the condenser of the heat pump.

FIG. **4** depicts a detailed view of the spider shaped distribution connector **13**.

FIG. **5** represents a schematic side view of the adsorption cell cluster according to FIG. **3**. In FIG. **5** it can be seen that on both ends of the elongated cluster of elongated adsorption cells heat transfer connectors are arranged connecting the annular heat transfer channels of each of the adsorption cells by means of the spider connector **15** to the T-heater connection **16**. The vapor conduits on the other hand are in this embodiment only connected to one of the sides of the elongated cell cluster. The vapor conduits may alternatively also be positioned at both ends of the elongated adsorption cells, since it can be favorable to have the vapor entering or exiting guided either along the relative hot or the relative cold side.

FIG. **6** depicts an arrangement of two adsorption cell clusters in a schematic perspective view. The first adsorption cell cluster **26a** is connected by means of the heat transfer T-connector **16a** to a heat transfer inlet manifold (or header) **20** and to a heat transfer outlet manifold **21**. The vapor manifold manifolds **18a** and **18b** are connected to the vapor manifold **25** through connectors **23** and **22** respectively. Both the conduits **23** and **22** are connected to the T-connector **24**, which connects these conduits to the vapor manifold **25**.

In FIG. **7**, a schematic process flow diagram is depicted of the heat transfer fluid circulation through the adsorption cell clusters **26a**, **26b**, **26c** and **26d** in a first mode of operation. In order to better elucidate the invention, the vapor flow conduits are left out. It is to be noted, however, that each of the adsorption beds **26a**, **26b**, **26c** and **26d**, is connected by means of vapor conduits and through a set of check valves to a condenser, a pressure release valve and an evaporator. Such arrangement can be found in heat pumps and refrigerators (see for further details FIG. **9**).

In FIG. **7**, a heater or heat exchanger **32** is arranged to an outlet conduit **34** feeding the heater or heat exchanger **32** with a relative hot heat transfer fluid, originating from the hot sides **39A** and **39B** of the reheated adsorption clusters **26A** and **26B** respectively or from the hot sides **39C** and **39D** of the reheated adsorption cell clusters **26C** and **26D** respectively, during their respective cooling modes. The heater or heat exchanger **32** is further connected to an inlet conduit **36** for guiding reheated heat transfer fluid to either the hot side **39A** and **39B** of adsorption cell clusters **26A** and **26B** respectively or the hot side **39C** and **39D** of the adsorption cell clusters **26C** and **26D** respectively during their respective heating mode.

The heater or heat exchanger **32** can for instance be a gas fired heater or a heat exchanger that is fed by a normal auxiliary heat transfer fluid, originating e.g. from a solar-thermal system. In FIG. **7**, the adsorption cell clusters **26A**

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and **26B** are in the mode of cooling down, whereas the adsorption cell clusters **26C** and **26D** are in a mode of heating up. The hot heat transfer fluid exiting the heater or heat exchanger **32** is guided by the three-way valve **27** through the inlet manifold **20c** to the adsorption cell clusters **26c** and **26d**. During this mode, the adsorption material is heated up in a specific way, with a rather steep temperature profile or front that is at the start of this mode close to the hot ends **39C** and **39D**. During the influx of hot heat transfer fluid at the hot end of the adsorption cell clusters, the temperature profile or front, also indicated as thermal wave, see U.S. Pat. No. 4,610,148 is pushed through the individual cells until it reaches the cold sides **40C** and **40D** of the adsorption cell clusters **26C** and **26D** respectively.

During the influx of the hot heat transfer fluid in the heat transfer channels **2A** of the adsorption cell clusters **26C** and **26D**, due to the rather steep temperature profile, relative cold heat transfer fluid is exiting the cold sides **40C** and **40D** of the adsorptions cell clusters **26C** and **26D**. The relative cold heat transfer fluid is forced through the outlet manifold **21A**, through the three way valve **29** and through the outlet conduit **38** to the cooler or heat exchanger **31**.

Although the heat transfer fluid originating from the adsorption cell clusters **26C** and **26D** is relatively cold, it needs to be further cooled in order to re-cool the adsorption cell clusters **26A** and **26C**.

By the application of the heat transfer fluid T-connectors **16** in combination with the three way valves **27-30**, only very limited amounts of heat is lost by mixing up cold and warm portions of heat transfer fluid. Each time, one arm of the T-connectors **16** and the thereto connected manifolds are switched in function, while the other arm and the thereto connected relevant manifolds are connected to a dead end conduit and thus idle. Thus in mode **1**, according to FIG. **7**, the outlet manifolds **21B** and **21C** are closed off, as well as the inlet manifolds **20A** and **20D**. Thus in mode **2**, as represented by FIG. **8**, the outlet manifolds **21A** and **21D** are closed off, as well as the inlet manifolds **20C** and **20B**. Since all the conduits **33-36**, manifolds **20A-D** and **21A-C** including the T-connectors **16** and the three way valves **27-30** are properly heat isolated, heat losses are reduced to a minimum.

When the temperature profile or front reaches the cold sides **40C** and **40D**, a heat detector (not shown) will provide a signal to a controller (not shown), which can turn the four three way valves **27**, **28**, **29** and **30** to switch. By switching the three way valves **27-30**, the system instantaneously switches in the second mode.

In the second mode, as shown in FIG. **8**, the adsorption cell clusters **26C** and **26D** are in the mode of cooling down, whereas the adsorption cell clusters **26A** and **26B** are in a mode of heating up. The hot heat transfer fluid exiting the heater or heat exchanger **32** is now guided by the three-way valve **27** through the inlet manifold **20D** to the adsorption cell clusters **26A** and **26B**. During this mode, the adsorption material is heated up in a the same way as the adsorptions cell clusters were in mode **1**, with a rather steep temperature profile or front that is at the start of this mode close to the hot ends **39A** and **39B**. During the influx of hot heat transfer fluid at the hot end of the adsorption cell clusters **26A** and **26B**, the temperature profile or front, also indicated as temperature wave, see U.S. Pat. No. 4,610,148 is pushed through the individual cells until it reaches the cold sides **40A** and **40B** of the adsorption cell clusters **26A** and **26B** respectively.

During the influx of the hot heat transfer fluid in the heat transfer channels **12A** of the adsorption cell clusters **26A** and

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26B, due to the rather steep temperature profile, relative cold heat transfer fluid is exiting the cold sides **40A** and **40B** of the adsorptions cell clusters **26A** and **26B**. When the temperature profile or front reaches the cold sides **40A** and **40B**, a heat detector (not shown) can provide a signal to a controller (not shown), which can turn the four three way valves **27**, **28**, **29** and **30** to switch. By switching the three way valves **27-30**, the system instantaneously switches back in the first mode, such that the cycle can start anew.

The heat exchanger or cooler **31** cools down the portion of the heat transfer fluid used for cooling the adsorption beds. The hot heat transfer fluid in the inlet of the adsorption beds **26c** and **26d** will be guided through the annular walls of the individual adsorption cells within the clusters **26c** and **26d** and will gradually heat up the adsorption material inside the inner walls **11** of the individual adsorption cells. Each of the arms of the T-connectors of the hot sides of the clusters are in fluid connection with a switching side of a first pair of three way valves, in such a way that the different arms of each individual T-connector is in fluid connection with the switching side of a different three way valve.

By heating up the adsorption material, the adsorbed vapor will be gradually released from the adsorption material. In the length wise direction of the individual adsorption cells a front of hot heat transfer fluid will slowly expel the cold heat exchanger fluid through the annular heat transfer channels within the individual cells towards the outlet manifold **21a**. This outlet manifold is connected to the heat transfer fluid three-way connection valve **29** towards the cooler/heat exchanger **31**.

In FIG. **9** a schematic representation of the tube side of the adsorber cells or clusters and the adsorbed refrigerant flow diagram is depicted. The tube sides of the clusters of adsorption cells **26A-D** are via manifolds **25A** and **25B** and through a set of check valves **41A**, **41B** and **42A**, **42B** connected to condenser **46** and an evaporator **49**. The condenser **46** is via conduit **47** and expansion valve **48** connected to the evaporator **49**.

During heating of the clusters of adsorption cells **26A** and **26B**, the refrigerant gas is at relative high pressure forced out of the adsorption material and will be guided by check valve **41A** and **41B** towards condenser **46**. In condenser **46**, heat is removed from the high pressure gas such that is condenses to a liquid. After exiting the condenser, the liquefied gas is chocked over expansion valve **46**, where the temperature and pressure of the gas drops considerably. At low pressure, the condensed gas will start to boil in the evaporator **49**, collecting heat from its surroundings in order to re-evaporate the gas. The low pressure refrigerant gas exiting the evaporator **49** will be guided through check valves **42A** and **42B** to that adsorber that is in its cooling mode, collecting and adsorbing the gas.

Although not shown, in order to further enhance the efficiency of the system, a counter flow heat exchanger may be integrated in the conduits **45** and **50**. Thus the relative warm coolant in conduit **45** can be cooled by the relative cold refrigerant from conduit **50** before it is condensed in condenser **46**.

The flow diagrams of FIGS. **7**, **8** and **9** are in practice combined, such that with the combined installation by means of an abundant relative low caloric heat source, a relative high thermal cooling action can be performed substantially without mechanical equipment other than a series of valves and check valves.

In an alternative embodiment, when the temperature profile seen along the length of the clusters **26A-D** or cells **1** is relative flattened (as a result of axial dispersion), the trigger

to switch flow, either switching to cooling down or switching to heating up may happen too soon for an efficient operation of the adsorber cells. Thus the Coefficient of Performance may be too low for economical service. In order to maximize the use of the heat of the heat transfer fluid, shortcuts may be integrated in both the hot and cold portions of the cycles. The clusters 26A, 26B or 26C and 26D to be cooled can be connected to the cooler 31 and the clusters 26C and 26D or 26A and 26B to be heated can be connected to the heat exchanger or heater 32. Thus substantially four modes of operation are possible. This can be performed in two ways, firstly by maintaining the flow directions in the shell sides of the clusters 26A-D or the cells 1 and secondly by switching the direction of flow when switching from cooling to heating and vice versa.

In FIG. 10A-D a first alternative with short cuts, without changing the direction of the flow in the clusters 26A-D is represented. A similar flow scheme is depicted in FIGS. 10E-10I, wherein only the arrangement of the individual elements is different, the flow lines are the same as in the FIGS. 10A-D. In FIG. 10A the first mode of the cycle is represented, in which the heat transfer fluid is pumped from heater 32 through three way valve 53 to cluster 26A, in which the adsorbing material is heated. The heat transfer fluid exiting the cluster 26A, is during the motion of the thermal wave through the cluster 26 still relatively cold and is guided through three way valve 55 to the cooler 31. Here the relative cold heat transfer fluid is additionally cooled. This cooled heat transfer fluid is guided through three way valve 56 to cluster 26C, which is in its cooling mode, thus adsorbing gas in the adsorbing material within its tubes. The heat transfer fluid exiting the cluster 26C is still relatively hot and is guided through three way valve 54 to the heater 32.

Thus cluster 26A is being heated, wherein a hot thermal wave front is moving upwards, and cluster 26C is cooled down, wherein a cold thermal wave front is moving downwards.

When a relative flattened (dispersed) thermal wave breaks through, at a certain moment the cycle is switched to the first shortcut mode, which is represented by FIG. 10B. The optimum moment in time of switching is described with reference to FIG. 12 herein below. During switching, the three way valves 54 and 55 are switched, resulting in that heater 32 and the cluster 26A are in a first separate cycle and cooler 31 and cluster 26C are in a second separate cycle. Thus cluster 26A is still further heated up, while its exit stream of heat transfer fluid now is guided back to heater 32 in stead of to the cooler 31. Meanwhile cluster 26C is still cooled down, while its exit stream is returned to the cooler 31 instead of to the heater 32.

At a moment the thermal wave is fully broken through and further heating of cluster 26A as well as further cooling of cluster 26C is impossible.

At that moment the cycle will be reversed, such that the cooled cluster 26C must be re-heated, the heated cluster 26A must be re-cooled. This can be performed by switching to the third mode of operation, as is represented in FIG. 10C.

In this figure, the cluster 26A is now cooled down, and the cluster 26C is now heated up. Once the relative flattened (dispersed) thermal waves in cluster 26A and 26C break through, the cycle is switched to a second shortcut mode, as represented in FIG. 10D. In this figure, the heater 32 and the cluster 26B form a third closed cycle, while the cooler 31 and the cluster 26A form a fourth closed cycle. When the full thermal waves break through in both clusters 26A and 26C, the system is switched again to the first mode of operation.

In the FIGS. 10A-10D, both the hot and cold thermal waves all travel in one direction through the clusters 26A and 26C, whereas in he embodiment of FIGS. 7 and 8, the thermal wave is sent back and forth within the clusters 26A-D. Accordingly the clusters 26A and 26C in FIGS. 10A-D no longer have a hot and a cold side.

Indeed it is possible also to send the thermal waves back and forth within the clusters, while still recovering losses in efficiency due to flattened (dispersed) thermal waves. In FIGS. 11A-11D the schematic process flow diagram for such operation is presented. In these diagrams the clusters are at each end provided with cross connectors in stead of T connectors.

In the first mode, as represented by FIG. 11A the cluster 26E is heated, while the cluster 26F is cooled. In cluster 26E, the heat transfer fluid flows upward, in cluster 26F, the heat transfer fluid flows downward. Once the thermal waves break through, the operation is switched to the second mode. In this first mode the thermal waves that break through are in fact a hot front reaching the cold side 40E of cluster 26E and simultaneously the cold front reaching the hot end 39F of cluster 26F. In the embodiment as represented by FIGS. 7 and 8, at this moment the flow within the clusters would have been reversed. Since however the thermal wave may be more flattened (dispersed), in order to gain the performance, in the second mode, cluster 26E is further heated and cluster 26F is further cooled, however the exiting flows are diverted. In this mode, as depicted in FIG. 11B, the exiting flow of cluster 26E is led to the heater 32B instead of to the cooler 31B and meanwhile the exiting flow of cluster 26F is guided to the cooler 31B instead of to the heater 32B.

When the thermal heat wave tails break through, the direction of flow in both clusters 26E and 26F is reverted. In this mode, which is represented by FIG. 11C, cluster 26F is heated, while cluster 26E is cooled. Now the flow direction in cluster 26E is directed downward and in cluster 26F is directed upward. Once in the third mode the thermal waves start to break through in the clusters 26E and 26F, the system is switched in its fourth mode, as represented in FIG. 11D. In this mode, cluster 26E and cooler 31B are coupled in a first cycle, and cluster 26F and heater 32B are coupled in one cycle.

When the tails of the heat waves break through, the system is switched back to its first operating mode.

The arrangement of valves and manifolds is designed to only have a small portion of conduits, wherein hot and cold heat transfer fluid needs to pass. Thus within the embodiments of the systems according to the invention, no single valve is faced with hot and cold het transfer fluid streams. Thus efficiency losses can be minimized.

The determination of the right moment to switch from the first mode to the second shortcut mode of the cycle depends on maximising the overall efficiency or the COP of the system.

It appears from validated modelling that indeed the thermal waves are rather flattened (dispersed), as is represented in FIG. 12. In this figure, the outflow temperatures of cluster 26A and 26C, as shown in FIGS. 10A-D and described hereinabove, are depicted in relation to the time the thermal wave is passing through these clusters. These exit temperatures are in theory the temperatures of the heat transfer fluid that can be used to heat or cool the other cluster. Before entering the other cluster, the temperatures of the heat transfer fluid are brought back to original levels in the cooler 31 and the heater 32. The more these temperatures deviate from the original temperature, the higher temperature difference need to be bridged and the more effort needs to be

put in. In the ideal situation the heat wave is very steep and the temperature deviations are relatively small and substantially constant during the first mode.

The solid line in FIG. **12** represents the temperature at the exit of cluster **26**A. Cluster **26**A is at time 0 hot and in the cooling down mode and cluster **26**C is cold and in the heating mode. The temperatures of cluster **26**A are discussed for several time intervals:

0-100 s. There is a linear decrease of temperature of the out flowing fluid. Because relative cold heat transfer fluid is flowing in, the first part of the cluster **26**A is cooled down rapidly. Significant adsorption occurs at that part of the adsorption bed so that the whole bed is depressurized. Because of this pressure decrease, the warm part of the adsorption bed will start to desorb. Heat of desorption is required, this lowers the temperature of the bed. Since the cell is built like a heat exchanger, the thermal fluid passing and exiting the cluster **26**A will also be cooled.

100-550 s. The cluster **26**A is at low pressure, gas flows into the adsorption material side of the cluster **26**A and is adsorbed. The out-flow temperature remains substantially constant at a sort of a 'plateau' for a while, but then gradually drops at 250 s. Indeed the results in FIG. **12** indicate that the thermal gradients are not as steep as expected and described in e.g. U.S. Pat. No. 4,610,148.

550-1200 s. The temperature of the heat transfer fluid flowing out of cluster **26**A is still lower than that of the heat transfer fluid flowing out of cluster **26**C.

At 550 s, the temperature of the heat transfer fluid flowing out of cluster **26**C becomes higher than that of the heat transfer fluid flowing out of cluster **26**A. At that point, the system should switch from the first mode into the second shortcut mode, as represented in FIG. **10**B.

At this very moment, it is less efficient to heat up the heat transfer fluid exiting cluster **26**A and to use it to further heat up cluster **26**C. More efficient is to cool down this heat transfer fluid and to reuse it in the very same cluster **26**A to further cool this cluster **26**A.

In all the operations of switching mode, as represented by FIGS. **7-11**, a further efficiency gain can be obtained when the pressure in the adsorption sides of the separate cells or the separate clusters is equalised between switching from adsorption to desorption and vice versa. Such an option requires an additional short cut line **62**B with a short cut valve **63**B which are represented in dashed lines in FIG. **9**.

From validated numerical simulations in coaxial shell and tube design, as depicted in the FIGS. **1,2** and **10**A-D a relation between the COP and the SCP could be obtained, as is plotted in a graph as depicted in FIG. **13**. In this figure on the abscises a combined parameter γ is plotted against the COP on the ordinate. The combined parameter γ is defined as

$$\gamma = SCP \cdot \frac{r^2}{\lambda_{ads}} \qquad (10)$$

Wherein λ_{ads} is the thermal conductivity of the adsorbing material and r is the (equivalent) radius of the adsorbing material in an elongated tube. From this figure it can be deduced that at a high value of γ, the COP tends to a value of 0.4, which represents a compressor with batch heating and cooling, where no thermal wave is present. It can further be deduced that with a small (equivalent) radius a relative high COP can be reached, although the SCP may suffer.

The COP and the SCP are generally desired quantities, dictated by technical specifications and commercial reasons. Once these are given and the specific adsorption material is chosen, from this plot, the (equivalent) radius of the adsorption material can be deduced.

The results of this plot imply:

The decrement in COP with increasing γ is caused by the occurrence of enlarged radial gradients at the position of the thermal wave where heat flows in or out of the adsorption material. These radial gradients are believed to reduce the steepness of the thermal wave, in effect the thermal wave becomes sort of smeared out in the elongated direction of the adsorption cell **1**, causing the exit temperature to decrease earlier in a hot cell and to increase earlier in a cold cell.

Enlarged radial gradients can be influenced by the three parameters: SCP, r and λ within the combined parameter γ in the following way:

Proportionally by the SCP since the SCP is directly related to the power input of the cell, and logically radial gradients are directly related to the power input.

Proportionally to the square of the (equivalent) radius of the adsorption material, the input power has to increase with the mass of the adsorption material within the cell in order to maintain the SCP constant, and the mass of the cell is proportional to the square of r.

Proportionally to the inverted radial thermal conductivity of the adsorption material. A higher conductive heat transport lowers the thermal gradients.

The COP is substantially not related to the length of the cell, as long as the cells remain elongated, wherein a length over diameter of at least 10 seems reasonable. Practically spoken, no difference in COP is obtained by either taking 20 cells of 1 m or 40 cells of 0.5 m. In both situations the SCP remains constant. However, the length of the cells does have a substantial effect on the power losses due to viscous pressure drop in the heat transfer fluid channel, as can be deduced from equation 9.

Accordingly a maximum COP is achieved at a minimal SCP, which is a known trade off. More interesting is that the thermal conductivity of the adsorption material should be high, less known is that it is far more important to reduce the (equivalent) radius of adsorption material. In this equation 10 minimising the (equivalent) radius of the adsorption material appears to have the highest impact on γ.

However a smaller (equivalent) radius of the adsorption material results in a larger number of cells. The number of cells can be calculated with:

$$N = \frac{P_{cooling}}{SCP \cdot \rho_{ads} \cdot \pi \cdot r^2 \cdot l_{cell}} = \frac{P_{cooling}}{\gamma \cdot \lambda_{ads} \cdot \pi \cdot \rho_{ads} \cdot l_{cell}} \qquad (11)$$

With this (equivalent) radius, and equation 4 a maximum diameter of the heat transfer fluid channel can be determined. In addition thereto, from the equation 9, a maximum pressure drop can be deduced. The pressure drop and the Biot number can now be plotted against the thickness of the heat transfer fluid channel, as is represented in FIG. **14**.

In this figure the pressure drop is scaled at the right ordinate, the Biot number is scaled at the left ordinate, the diameter of the annular heat transfer fluid channel is scaled at the abscises. Line L**1** represents the calculated pressure drop, line L**2** represents the calculated Biot number. From

this plot, it can be deduced weather a diameter is given for which on the one end the power losses due to hydrodynamic pressure drop is not too high and on the other hand the Biot number is not too low.

This plot depicts that for the combination of amorphous carbon as adsorbents, NH_3 as refrigerant or adsorbing gas and water as a heat transfer fluid, in a concentric tube design, a working window is provided. This window allows the diameter of the heat transfer fluid channel to be between approximately 0.1 and 0.4 mm.

In case thermal oils are used as heat transfer fluid, due to the relative low thermal conductivities, Biot requires an extremely narrow heat transfer fluid channel, leading to unacceptable pressure drop. In order to still provide a working range, radial heat conductors can be inserted within the heat transfer channel.

The thermal conductivity of the heat transfer fluid can be chosen between approximately 0.1 and 10 W/mK, wherein for possible fluids, like mercury, the thermal conductivity is approximately 7-10 W/Km, and of water is approximately 0.3-1.0 W/Km. Thermal oils can have thermal conductivity of 0.1-0.6 W/Km. Accordingly workable ranges may be between 0.1 and 10 W/Km, however predominantly may lie between 0.1 and 1 W/K m.

For the cycle time the following equation is given:

$$t_{cycle} = \frac{\Delta x_{net} \cdot \Delta h}{SCP} \qquad (12)$$

Wherein t_{cycle} is the total cycle time of a sorption cell or cluster i.e. the total cycle time for the ad- and desorption mode, Δh is the enthalpy change [J/g] of the refrigerant gas that is providing the cooling power (typically 1.2 MJ/kg for ammonia) and Δx_{net} is the net amount of gas that is ad- and desorbed from the carbon in one ad- and desorption cycle, expressed in gram gas per gram adsorption material (typically 0.15 gram ammonia per gram carbon).

In FIG. **15**, an example of such radial conductors is presented. In this figure a corrugated thin metal sheet **61** is attached around the inner wall **12** of the adsorption material **10**.

In FIG. **16** a further alternative geometry of the adsorption material **10**, the inner wall **12** and the outer wall **11** is presented. In this embodiment, a series of tubes containing adsorption material are jacketed by an outer wall **11**. In between the separate adjacent tubes, the outer wall can be welded or soldered together. An advantage of this arrangement is that higher capacity coolers or heat pumps need a substantial amount of adsorption material, which can be more rapidly manufactured when a number of channels are connected and produced in one step.

Alternatively, as is depicted in FIG. **17**, also virtual three dimensional structures can be made, where the heat transfer fluid channels are virtually surrounded by adsorption material. Infinitive shapes of such three dimensional structure are possible, though the diameter of the heat transfer fluid channel should substantially not vary within the cluster, neither in the elongated direction nor in its cross sectional direction, since "false flows" might rapidly impair the efficiency of the adsorption compressor. Indeed in these geometries the relative dimensions of the heat transfer fluid channels and the dimensions of the adsorption material must still obey equation 4 or its geometrical equivalent.

In order to improve the radial conductivity of the adsorption material, e.g. radial conductors can be inserted in the

adsorption material. For instance heat conductive lamellae **62**A might be arranged within the adsorption material **10**, in between individual adsorption units **68**B, which are typically cylindrical in shape, for instance in the form of pills, as is depicted in FIG. **18**A. Other solutions might be to integrate heat conductive carbon fibres within the amorphous carbon. These carbon fibres might include carbon nanofibres such as bucky tubes.

In another embodiment, the adsorption cell or cluster thereof of the invention comprises units **68**B) and conductive lamellae **62**A) that are formed by a pill that is at least partly surrounded by a cup from a heat conductive material, wherein the cup contains the pill. The closely fitting cups are preferably made of the same material as the cell wall, typically stainless steel, to minimize the effects of thermal expansion mismatch between the cell and the cups. A separate thin sheet of high-conductive material (such as aluminum or graphite) can be added on one or both sides of the bottom of the cup to ensure a good heat transfer from the cell wall into the adsorption pills. This embodiment is schematically illustrated in FIG. **35**.

It is also possible to provide the cup **111**) entirely of the conductive material, such as aluminum.

The cup may contain one or more openings **70** that serve as a channel for the refrigerant.

Alternative adsorbent materials that may be applied within the scope of the invention are activated carbons, zeolites, silica gels and metal organic frameworks. The refrigerants that alternatively may be applied are carbon dioxide, hydroflorocarbons, (HFC's such as R-134a refrigerant), hydrochlorofluorocarbons (HCFC's such as R-123 refrigerant), water, methanol, ethanol, ethane, propane, isobutene, isopentane, propylene, formaldehyde and vinyl fluoride. Other suitable refrigerants may also be applied within the scope of the invention.

In FIG. **18**B the individual adsorption pills **68**B are provided with radial micro channels **69** in order to enhance the permeability of the adsorption material. In the case the permeability of the adsorption material becomes to low, these channels may prevent the radial transport of the refrigerant gas or vapor as becoming a limiting factor in the efficiency of the adsorption compressor. The micro channels can support the transport of refrigerant to and from the refrigerant channel **70**.

During manufacture of the adsorption pills **68**B, the shape of the radial micro channels **69** may already be present in the adsorption pill press mould, such that no machining of the adsorption pills need to be performed afterwards. Alternatively, these micro channels **69** may be machined or etched into the adsorption material. These micro channels **69** may be applied at one or at both facing ends of the individual pills **68**B.

FIG. **37** shows a part of an example of an embodiment of adsorption cell according to invention in exploded view. The adsorption cell **1** is suitable for a thermal wave operated adsorption compressor and comprises an elongated heat transfer fluid (HTF) channel **2**A defining a heat transfer fluid flow path having an axis and a length L. In the shown example the HTF channel **2**A is straight, but the invention also includes embodiments in which the adsorption cell may have a HTF channel **2**A that extends along a curved path. This may be advantageous in view of compactness. However, from an ease of manufacturing point of view, straight HTF channels **2**A are preferred. The adsorption cell **1** further comprises at least one solid adsorption material housing **12** that extends in the heat transfer fluid channel **2**A and that defines an adsorption material chamber. In the exemplary

embodiment shown in FIG. 37, the adsorption material housing 12 is formed by an inner shell 11 in the form of a tube with a limited heat conduction, for example stainless steel. The HTF channel 2A is bounded by an outer shell 11 in the form of an outer tube 11 that may be manufactured from stainless steel as well. In the exemplary embodiment of FIG. 37, the two shells 11, 12 are co-axial. In an alternative embodiment, the outer shell may define a HTF channel in which the flow direction of the heat transfer fluid is along an HTF channel axis of that channel and in which a plurality of adsorption material housings 12 are placed in the HTF channel that have an longitudinal axis that extends perpendicularly or at an acute angle relative to the HTF channel axis. In such an embodiment, the plurality of adsorption material housings 12 will be present along the length of the HTF channel 2A. The adsorption cell further includes solid adsorption material 10 that is accommodated in the at least one solid adsorption material chamber and that is in direct heat transferring contact with heat transfer fluid that, in use, flows through the heat transfer fluid channel 2A. The solid adsorption material 10 comprises a stack of units 150, each unit comprising a pill 150 of adsorption material. Each pill 150 includes a top 152, a bottom 154 and at least one side 156. Each unit is associated with a cup 158 from a heat conductive material. The heat conductive material may, for example, be aluminum, copper or the like. The pill 150 of the unit is at least partly surrounded by the associated cup 158. Each cup includes a cup bottom wall 160 forming a heat conductive lamella extending between the pill 150 of the unit and a pill 150' of an adjacent unit 150' in the stack of units. Parts of the cup bottom wall 160 are in abutting contact with associated parts of the bottom of the pill 150 of the unit 150 and parts of the cup bottom wall 160 are in abutting contact with associated parts of the top of the pill 150' of the adjacent unit. Preferably, the parts form a major part of the total surface area of the bottom 154 and the top 152 of the pill 150. However, cross grooves may be present in the top 152 and or bottom 154 and chamfered or rounded perimeter edges of the pill 150 may be provided both for distributing refrigerant fluid over the pill 150. These cross grooves and rounded or chamfered perimeter edges do not form part of the abutting parts mentioned above. Each cup also includes a jacket wall 162 of which at least a part is in abutting contact with an inner side of the solid adsorption material housing 12. The relatively large contact area between the jacket wall 162 and the inner side of the solid adsorption material housing 12 promotes heat transfer between them.

The surface conformity and roughness of the associated parts of the bottom 154 of the pill 150 of the unit and of the associated parts of the top 152' of the pill 150' of the adjacent unit on the one hand and of the abutting parts of the cup bottom wall 160 on the other hand are such that any gap between the abutting parts is less than 30 micron, preferably less than 10 micron.

By virtue of the fact that the gaps, if present, are very small, the heat transferring contact between the cup bottom wall 160 and the pill 150 that is enclosed by the cup 158 and the pill 150' that is below the cup 158 is at least as good or even better as the heat transfer within the adsorption material 10 of the pills 150, 150'. The small size of the gaps preferably is obtained by very accurate manufacturing of the cups and the pills. However, it is also feasible that any gaps are closed or minimized by interpositioning glue, a cloth or a sheet between the bottom wall 160 of the cup 158 and the associated pill 150.

Preferably, a surface conformity and roughness of the part of the jacket wall 162 that is in abutting contact with the inner side of the solid material adsorption housing 12 on the one hand and a surface conformity and roughness of the inner side of the solid material adsorption housing 12 on the other hand are such that any gap between the abutting part of the jacket wall 162 and the inner side of the solid adsorption material housing 12 is less than 30 micron, preferably less than 10 micron.

Again, such a condition provides a heat transfer resistance over any gap between the cup and the adsorption material housing 12 that is less than the heat transfer resistance in the radial direction of the combination of the cup 158 and adsorption material 10.

In order to obtain an advantageous combination of SCP and COP, the pill has a characteristic dimension r in a plane that is perpendicular to the axis of the heat transfer channel 2A, which characteristic dimension is smaller than 1 cm, preferably smaller than 0.5 cm, more preferably smaller than 0.4 cm.

In order to promote a transport of refrigerant fluid over the length of the stack of units 150, at least one axial refrigerant channel 70; 164 is provided that extends along the stack of units 68B, 150. To that end, in an embodiment each pill 68B; 150 may have at least one refrigerant groove 164 in the side 156 that extends in the direction of the stack of units. Each cup 111; 158 may have a hole 166 in the bottom wall 160 or a notch in the jacket wall 162 of which hole 166 or notch the cross sectional area substantially corresponds with the cross sectional area of the refrigerant groove 164. The refrigerant grooves 164 of the pills 68B; 150 are aligned relative to each other and the holes 166 or notches of the cups 111; 158 are aligned relative to the refrigerant grooves 164 so that they together form the at least one refrigerant channel 70.

To facilitate alignment of the pill 150 within the cup 158, an embodiment may be provided in which the pill 150 and the cup 158 both have a co-operating structural feature 172, 168 that prevent rotation of the pill 150 within the cup 158 and that define the rotational position of the pill 150 within the cup 158.

In a first elaboration of that embodiment the structural feature in the cup 158 may include a dent forming a cup projection 168. The associated pill 150 includes an associated pill indentation 172. The refrigerant groove 164 of the pill 150 and the hole 166 or notch in the cup 68B; 150 are aligned when the pill indentation 172 accommodates the associated cup projection 168. In the example shown in FIGS. 37-42, the projection 168 is formed in the bottom wall 160 of the cup and the indentation 172 is formed in the bottom of the pill 150. It is clear that the indentation 172 may alternatively be provided in the side 156 of the pill. This may be an indentation that is solely intended for that purpose but it may also be a notch or a part of the notch that may serve to form a refrigerant groove. In such case, the projection 168 will formed in the jacket wall 162 or in a notch that is present in the jacket wall 162.

In a second, alternative further elaboration, the structural feature of the cup 158 may include a jacket wall 162 with a non-circular cross section in a plane parallel to the bottom wall, preferably an elliptical cross section. The structural feature of the pill 150 may include a non-circular cross section in a plane parallel to the bottom or top of the pill 150, which pill cross section corresponds with the cross section of the jacket wall 162. In stead of an elliptical cross section, the cross section may be circular with an indent, or may be poly-angular.

To facilitate alignment of the units relative to each other, an embodiment is provided in which the cup **158** includes a structural feature that engages a neighboring pill **150'** or cup **158'** or that engages a co-operating structural feature **170** of the adsorption material housing **12**.

In a further elaboration, the structural feature of the cup **158** may include at least one lip **170** adjacent the hole **166** or notch, which lip **170** engages a wall delimiting the refrigerant groove **164'** of a neighboring pill **150'** or engages a notch, a recess or cut-away in the jacket wall **162'** of the neighboring cup **158'**.

In an alternative further elaboration, the structural feature of the cup **158** may include a jacket wall **162** with a non-circular cross section in a plane parallel to the cup bottom wall **160**, preferably an elliptical cross section, wherein the adsorption material housing **12** includes a non-circular cross section in a plane parallel to the cup bottom wall **160**, which non-circular adsorption material housing cross section corresponds with the cross section of the jacket wall **162**. A slightly elliptical cross section has the advantage of a circular cross section of being strong and able to withstand large pressure differences between the inside and the outside of the inner shell **12**. The additional advantage that is obtained with an elliptical cross section is that a correct orientation of the units **150** is obtained so that the refrigerant grooves **164** and the holes **166** or notches in the cups are aligned and the refrigerant channel **70** extends along the stack of units. Thus refrigerant fluid may be transported with a minimal resistance.

In order to reduce the length over which the refrigerant fluid has to pass through adsorption material **10**, it is preferred that one or more cross channels **69**; **186** are present in said pill **68B**; **150** that extend substantially perpendicularly to the refrigerant channel **70**, **164** and that are in fluid connection with the axial refrigerant channel **70**, **164**. The cross channels guide the refrigerant fluid with relatively low resistance over the entire radial area of the pill **150**.

In an embodiment, of which an example is shown in FIGS. **37-42**, the cross channels **69**; **186** may formed by grooves in the top **152** and/or bottom **154** of the pill **68B**, **150**.

In an embodiment, an edge **176**, **178** formed by the side **156** of the pill **150** and the bottom **154** and/or the top **152** may be rounded or chamfered to form the at least one perimeter channel **180**, **182**. The dimension of the rounded or chamfered edge at least partly determine the cross sectional area of the perimeter channel or channels **180**, **182**. The perimeter channel or channels **180**, **182** promote the distribution of refrigerant fluid over the entire surface of pill **150**. Thus adsorption and desorption efficiency are improved.

In an embodiment, an edge **188** between the jacket wall **162** and the cup bottom wall **160** may be rounded or chamfered. Thus the cup **158** will have some flexibility in that the radius of the jacket wall **162** may vary a little to accommodate manufacturing tolerances of the cup and the adsorption material housing **12**. Even a more complicated wall structure may be included at the juncture between the bottom wall **160** and the jacket wall **162**. That more complicated structure has the object of providing some radial play to the jacket wall **162**. An example could be some sort of bellow structure.

In an embodiment in which the heat transfer resistance within the material is balanced with the other heat transfer resistances of the cell, the axial length of an individual pill **150** is in the range of 1.5-5 mm, preferably in the range of 2-3 mm. Preferably, the diameter of an individual pill **150** is

in the range of 6-20 mm, more preferably in the range of 8-10 mm. With these dimensions the wall thickness of the cup bottom wall **160** and the jacket wall **162** is preferably less than 300 micron, more preferably less than 150 micron. With such wall thicknesses, the heat conduction resistance within the cup is not the limiting factor in the heat resistance of the entire cell. The advantage of such small wall thicknesses is that the thermal mass that has to be heated and cooled during the use of the cell is minimized which is of importance for the efficiency of the adsorption cell **1**.

For an embodiment in which the direction of the stack of units is parallel to the flow direction of heat transfer fluid within the cell, it is preferred, in order to maintain a thermal wave having a steep thermal front within the adsorption cell, that a height of the jacket wall **162** of the cup **111**; **158** is less than thickness of the pill **150** which is defined by the greatest distance between the bottom **154** and the top **152** of the pill **150**, so that neighboring cups **111**; **158** of the stack of units do not contact each other. Thus the thermal wave will be more stable in operation of the adsorption cell **1**.

As described before, a cluster may be provided comprising a matrix of adsorption cells **1**. The HTF channels **2**, **3** of the individual adsorption cells are on both distal ends in fluid connection with a HTF manifold **13**. The refrigerant channels **70** of the individual adsorption cells are on one or both distal ends in fluid connection with a refrigerant manifold **18**. See in this respect FIGS. **3-5** and **20-27**.

The disclosure also relates to an adsorption compressor, suitable for thermal wave operation. The adsorption compressor may comprise:

at least one first cluster **26A**, **26B** of adsorption cells **1**;
at least one second cluster **26C**, **26D** of adsorption cells **1**;
a refrigerant circuit including:
  a condensor **46** having a condensor inlet and a condensor outlet;
  an expansion valve **48**;
  an evaporator **49** having an evaporator inlet and an evaporator outlet, the evaporator inlet being connected to condensor outlet via the expansion valve **48**; and
  an assembly of refrigerant valves **41A**, **41B**, **42A**, **42B** that is configured to alternatively connect the refrigerant manifold **25A** of the first cluster **26A**, **26B** and the refrigirant manifold **25B** of the second cluster **26C**, **26D** to the inlet of the condensor **46** and the outlet of the evaporator **49**;
a heat transfer fluid circuit including:
  a first heat source **32** having the function of a HTF heater;
  a second heat source **31** having the function of a HFT cooler and having a lower temperature than the first heat source **32**;
  a HTF valve assembly **27-30**; **53-58** that is configured to be switched to conduct heat transfer fluid between the HTF manifolds **20a-d**, **21a-d** of the at least two clusters and the HTF cooler **31** and the HTF heater **32**;
  at least one pump **37**, **38**; **P1-P4** for pumping around heat transfer fluid;
an electronic controller configured to control the HTF valve assembly **27-30**; **53-58** to provide four modes of operation in which the heat transfer fluid can be pumped around:
  a first mode wherein a single circuit of heat transfer fluid is arranged through the HTF heater **32**, the first cluster **26A**, **26B**, the HTF cooler **31**, the second cluster **26C**, **26D** and back in the HTF heater **32**;

a second mode comprising two separated shortcut circuits: a first one in which heat transfer fluid flows from the HTF heater **32** to the first cluster **26A**, **26B** and returns to the HTF heater **32**, and a second one in which heat transfer fluid flows from the HTF cooler **31** to the second cluster **26C**, **26D** and returns to the HTF cooler **31**;

a third mode wherein a single circuit of heat transfer fluid is arranged from the HTF heater **32** to the second cluster **26C**, **26D**, to the HTF cooler **31** and via the first cluster **26A**, **26B** back again in the HTF heater **32**; and

a fourth mode comprising two separated shortcut circuits: a first one in which the heat transfer fluid flows from the HTF heater **32** to the second cluster **26C**, **26D** and back in the HTF heater **32**, and a second one in which heat transfer fluid flows from the HTF cooler **31** to the first cluster **26B**, **26C** and returns to the HTF cooler **31**.

Such a adsorption compressor may, for example, be applied in a method to operate such an adsorption compressor, more specifically of cooling or heating e.g. by using a relative low caloric heat such as a solar boiler or a waste heat stream or a high caloric heat source such as a gas flame may comprise the following steps to be executed in any suitable order:

a) providing an adsorption compressor as described above,

b) heating in a first mode the adsorption material **10** in a first cluster **26A** by gently pumping hot heat transfer fluid exiting from a HTF heater **32** in a laminar flow through the heat transfer fluid channel **2A** of the adsorption cells **1** of cluster **26A**, such that a substantially steep decreasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells **1** within the first cluster **26A**, wherein the adsorbed refrigerant is desorbed from adsorption material **10** of the first cluster **26A** at relative high pressure, forced through check valve **41A** towards condenser **46**, condensed and forced through expansion valve **48** and left to evaporate and perform cooling action in evaporator **49**,

c) cooling during step b in a first mode the adsorption material **10** in a second cluster **26C** by gently pumping cold heat transfer fluid exiting from a HTF cooler **31** in a laminar flow through the heat transfer fluid channel **2A** of the adsorption cells **1** of cluster **26C**, such that a substantial steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells **1** within the second cluster **26C**, wherein the refrigerant is adsorbed by the adsorption material **10** of the second cluster **26C** at relative low pressure, originating from the evaporator **4** through check valve **42A**,

d) switching at a predetermined moment, to a second mode, cooling the adsorption material **10** in a first cluster **26A** by gently pumping cold heat transfer fluid exiting from a HTF cooler **31** in a laminar flow through the heat transfer fluid channel **2A** of the adsorption cells **1** of cluster **26A**, such that a substantially steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells **1** within the first cluster **26A**, wherein the refrigerant is adsorbed by the adsorption material **10** of the first cluster **26A** at relative low pressure, originating from the evaporator **4** through check valve **4 IB**,

e) heating during step d in the second mode the adsorption material **10** in a second cluster **26C** by gently pumping hot

heat transfer fluid exiting from a heater **32** in a laminar flow through the heat transfer fluid channel **2A** of the adsorption cells **1** of cluster **26C**, such that a substantially steep decreasing heat profile in axial direction, the thermal wave is maintained and gently pushed along the length of the elongated adsorption cells **1** within the second cluster **26C**, wherein the adsorbed refrigerant is desorbed from adsorption material **10** of the second cluster **26C** at relative high pressure, forced through check valve **42B** towards condenser **46**, condensed and forced through expansion valve **48** and left to evaporate and perform cooling action in evaporator **49**;

f) switching back in the first mode and repeating steps a-f.

In FIG. 19 a buffer container comprising adsorption material **10** is integrated in the refrigerant loop of FIG. 9. The amount of refrigerant in the loop can be adjusted by adjusting the temperature of the buffer container **63A**. For this a temperature controller **65** can regulate a valve **68A** in order to maintain the temperature at a predetermined value. By adjusting the amount of refrigerant inside the loop, the pressure in the condenser **46** and the evaporator **49** can be changed, thus changing the boiling and condensation temperature. Thus an elegant way of setting these temperatures can be obtained. Adjusting the expansion valve **48** can also be performed in order to adjust the relative pressures and temperatures in both the evaporator **49** and the condenser **46**.

In FIGS. 20-23B an alternative adsorption cell cluster **26** is depicted. In this adsorption cell cluster **26** a matrix of 10×10 parallel adsorption cells **1** is arranged in between two distribution elements **71** and **72**. The distribution elements **71** and **72** comprise a set of three plates **75**, **76** and **77**.

The first plate, the refrigerant conduit plate **75** comprises a refrigerant gas opening **73** for connecting a refrigerant manifold **78** to a refrigerant conduit **22**, **25** leading to the refrigerant loop as represented e.g. in FIG. 9 or 19. The refrigerant manifold **78** is machined or etched out of the material of the refrigerant conduit plate **75**. The refrigerant manifold **78** is in fluid connection with ten refrigerant sub manifolds **79**. The sub manifolds **79** are separated from each other by separation ribs **81**. In the sub manifolds **79** refrigerant guiding stubs are arranged for guiding the refrigerant in and out the inner tube **12** of the adsorption cells **1**.

The manifold **78** and the sub manifolds **79** are closed of by a lower side of the heat transfer conduit plate **76**. The top side of the heat transfer conduit plate **76** comprises a heat transfer fluid manifold **82**, which can be connected via heat transfer fluid opening **74** to a heat transfer fluid T-connector **16**. The manifold **82** is in fluid connection with ten heat transfer fluid sub connectors **83**. These sub manifolds **83** are in fluid connection with the annular heat transfer fluid channels **2A** of the individual adsorption cells **1**.

The manifold **82** and the sub manifolds **83** are closed by closing plate **77**. The closing plate **77** comprises openings for connecting the outer cylindrical wall **11** to the closing plate **77**.

The plates **75**, **76** and **77** can be interconnected by means of gluing, soldering of welding. The outer **11** and inner **12** cylindrical walls of the individual adsorption cells can similarly be welded, glues and/or soldered to the plates **77** and **76** respectively.

In the schematic cut out view of FIG. 23B, the arrangement of the three plates is depicted in more detail. In this figure, the outer cylindrical walls **11** of the individual adsorption cells **1** are connected to the openings in closing plate **77**. The ends of the outer cylindrical walls **11** are substantially flush with the inner face of the closing plate **77**.

33   34

The inner cylindrical walls **12** extend further and are connected in the connecting openings **85**A of the heat transfer fluid conduit plate **76**. Thus a fluid connection can be obtained between the heat transfer fluid sub manifolds **83** and the annular heat transfer fluid channel **2**A.

The ends of the inner cylindrical wall **12** of the individual adsorption cells are connected with the heat transfer conduit plate **76**. The ends of the inner cylindrical walls **12** are substantially flush with the upper face of the heat transfer fluid conduit plate. Thus a fluid connection can be obtained between the refrigerant sub manifolds **79** and the adsorption material **10**.

In FIG. **24**, an alternative arrangement of the distribution elements of the clusters is depicted. Separate plates **91**, **93**, **94** and gasket **92** are held together by a set of bolts **90**. In this arrangement, a closing plate **91** is provided with a series of reinforcement ribs **89** and reinforcement rings **95**. These ribs **89** and rings **95** provide structural integrity to the closing plate **91** and give it the strength to withstand the pressures of the refrigerant gas. Through the reinforcement rings **95** of the closing plate, the bolt bores **97** in gasket **92**, bolt bores **103** in the twin conduits plate **93** and the bolt bores **104** in the closing plate **94** bolts can be placed.

The twin conduit plate **93** is at its upper side provided with a refrigerant manifold **100** and at it lower side with a heat transfer fluid manifold **106**. These manifolds **100** and **106** can be machined out of the material of the twin conduits plate **93** or may alternatively be etched in the material. In the refrigerant manifold **100** considerable pressure might be present, up to approximately 20 bar. In order to contain the refrigerant inside the manifold and the system, a gasket can be placed between the twin conduits plate **93** and the closing plate **91**.

Although in the embodiment shown in FIGS. **26**A-D, a single manifold for both the heat transfer fluid and the refrigerant is depicted, alternatively also the arrangement with one manifold and separate sub manifolds can be applied, as is performed in the embodiments shown in FIGS. **22**A-C.

Alternatively a second gasket may be applied in between the twin conduits manifold and the closing plate **94**, in order to contain the heat transfer fluid.

In FIGS. **27**A and **27**B, a detailed cut open view is depicted of the cluster according to FIG. **24**. In this arrangement the heat transfer fluid channels **2**A of the individual adsorption cells are in fluid connection with the heat transfer fluid manifold **106**, and the adsorption material **10** is in fluid connection with the refrigerant header **100**.

The refrigerant header **100** is connected to the refrigerant conduit **86** which can be in fluid connection with the refrigerant loop as represented in FIG. **9** or **19**. The heat transfer header **106** is in fluid contact with the heat transfer conduit **87**, which is connected to the stem of a T-connector **88**.

Thus these clusters **26** can be integrated in the schematic flow diagrams as depicted in FIGS. **7-9**, **10**A-I, replacing the clusters **26**A-D. The cluster **26** can similarly be integrated in the process flow diagram according to FIG. **11**A-D, however in that case, the T-connectors **88** need to be replaced with cross connectors in order to fit in. In order to provide simultaneously moving thermal waves within one cluster, the predominant flow resistance should remain within the heat transfer channels **2**A. This means that the heat transfer fluid manifolds **82**, **106** need to be designed such that their flow resistance is at least an order of magnitude less than the overall flow resistance of all heat transfer fluid channels **2**A of all the cells within one cluster.

The refrigerant connections of the clusters can be at one or at two sides as is explained hereinabove.

The T-connectors in the heat transfer fluid conduits may be replaced by two heat transfer exits of manifolds **82**, **106** at each end of the cluster.

The plates **75-77**, **91-95** can be glued together, welded, soldered and/or a combination thereof. The cylindrical walls can be glued, shrink fitted, welded, soldered or screwed in or onto the plates.

Although the matrix of adsorption cells **1** is presented as a squared matrix, alternative arrangements are similarly possible, such as a honeycomb type of arrangement.

The present invention can be applied in a large variety of fields, in particular when waste heat is available, ranging from air conditioners, such as in automotive applications, in particular trucks; to refrigerators and other applications.

EXAMPLE

An experimental set-up was built to verify the performance improvements resulting from the present invention method of operation of the thermal wave, in combination with the described adsorption compressor bed suitable for thermal wave operation. The set-up consists of the following system components:

Two adsorption compressor beds, each made up of two clusters of eight adsorption cells as depicted in FIG. **6**B.

A HTF system with heater, cooler and four three-way valves, connected as depicted in FIG. **10**, which can be switched according to FIG. **10**F-**10**I.

A refrigerant loop incorporating check valves, condenser, evaporator and flow restriction as depicted in FIG. **9**.

A control system suitable to adjust the three-way valves, and to measure the relevant temperatures, pressures, flows and powers.

With this experimental set-up the claimed method of operation of the thermal wave was clearly demonstrated, and the expected heat pump operation was verified, resulting in an improved COP in combination with a high SCP. FIG. **36** demonstrates a typical measurement of the resulting entrance **112**, **114** and exit **113**, **115** temperatures of the two adsorption beds as a function of time. The depicted area X is proportional to the amount of heat that is regenerated between the two beds in this cycle. Note that in this particular measurement a temperature difference remains at the end of the cycle, which is the result of poor thermal isolation of the compressor beds in this experimental set-up.

The invention is to be understood not to be limited to the exemplary embodiments shown in the figures and described in the specification. Various modifications are considered to be variations that are part of the framework, the spirit and the scope of the invention outlined in the claims.

The invention claimed is:

1. Adsorption cell suitable for a thermal wave operated adsorption compressor comprising:

an elongated heat transfer fluid (HTF) channel defining a heat transfer fluid flow path having an axis and a length;

at least one solid adsorption material housing extending in the heat transfer fluid channel defining an adsorption material chamber;

solid adsorption material that is accommodated in the solid adsorption material chamber and that is in direct heat transferring contact with heat transfer fluid that, in use, flows through the heat transfer fluid channel, wherein said solid adsorption material comprises a stack of units, each unit comprising:

a pill of adsorption material, each pill including a top, a bottom and at least one side; and

each unit being associated with:

a cup from a heat conductive material, the pill of the unit being at least partly surrounded by the associated cup, each cup including:

a cup bottom wall forming a heat conductive lamella extending between the pill of the unit and a pill of an adjacent unit in the stack of units, parts of the cup bottom wall being in abutting contact with associated parts of the bottom of the pill of the unit and parts of the cup bottom wall being in abutting contact with associated parts of the top of the pill of the adjacent unit; and

a jacket wall of which at least a part is in abutting contact with an inner side of the solid adsorption material housing;

wherein the surface conformity and roughness of the associated parts of the bottom of the pill of the unit and of the associated parts of the top of the pill of the adjacent unit on the one hand and of the abutting parts of the cup bottom wall on the other hand are such that any gap between the abutting parts is less than 30 micron, preferably less than 10 micron.

2. The adsorption cell according to claim 1, wherein a surface conformity and roughness of the part of the jacket wall that is in abutting contact with the inner side of the solid material adsorption housing on the one hand and a surface conformity and roughness of the inner side of the solid material adsorption housing on the other hand are such that any gap between the abutting part of the jacket wall and the inner side of the solid adsorption material housing is less than 30 micron, preferably less than 10 micron.

3. The adsorption cell according to claim 1, wherein the pill has a characteristic dimension r in a plane that is perpendicular to the axis of the heat transfer channel, which characteristic dimension is smaller than 1 cm, preferably smaller than 0.5 cm, more preferably smaller than 0.4 cm.

4. The adsorption cell according to claim 1, wherein at least one refrigerant channel is provided that extends along the stack of units.

5. The adsorption cell according to claim 4, wherein each pill has at least one refrigerant groove in the side that extends in the direction of the stack of units, wherein each cup has a hole in the bottom wall or a notch in the jacket wall of which hole or notch the cross sectional area substantially corresponds with the cross sectional area of the refrigerant groove, wherein the refrigerant grooves of the pills are aligned relative to each other and wherein the holes or notches of the cups are aligned relative to the refrigerant grooves so that they together form the at least one refrigerant channel.

6. The adsorption cell according to claim 5, wherein the pill and the cup both have a co-operating structural feature that prevent rotation of the pill within the cup and that define the rotational position of the pill within the cup.

7. The adsorption cell according to claim 6, wherein the structural feature in the cup includes a dent forming a cup projection, wherein the associated pill includes an associated pill indentation, wherein the refrigerant groove of the pill and the hole or notch in the cup are aligned when the pill indentation accommodates the associated cup projection.

8. The adsorption cell according to claim 6, wherein the structural feature of the cup includes a jacket wall with a non-circular cross section in a plane parallel to the bottom wall, preferably an elliptical cross section, and wherein the structural feature of the pill includes a non-circular cross

section in a plane parallel to the bottom or top of the pill, which pill cross section corresponds with the cross section of the jacket wall.

9. The adsorption cell according to claim 6, wherein the cup includes a structural feature that engages a neighboring pill or cup or that engages a co-operating structural feature of the adsorption material housing.

10. The adsorption cell according to claim 9, wherein the structural feature of the cup includes at least one lip adjacent the hole or notch, which lip engages a wall delimiting the refrigerant groove of a neighboring pill or engages a notch, a recess or cut-away in the jacket wall of the neighboring cup.

11. The adsorption cell according to claim 9, wherein the structural feature of the cup includes a jacket wall with a non-circular cross section in a plane parallel to the cup bottom wall, preferably an elliptical cross section, wherein the adsorption material housing includes a non-circular cross section in a plane parallel to the cup bottom wall, which non-circular adsorption material housing cross section corresponds with the cross section of the jacket wall.

12. The adsorption cell according to claim 4, wherein one or more cross channels are present in said pill that extend substantially perpendicularly to the refrigerant channel and that are in fluid connection with the axial refrigerant channel.

13. The adsorption cell according to claim 12, wherein the cross channels are formed by grooves in the top and/or bottom of the pill.

14. The adsorption cell according to claim 1, wherein an edge that is formed by the side of the pill and the bottom and/or the top is rounded or chamfered to form the at least one perimeter channel.

15. The adsorption cell according to claim 1, wherein an edge between the jacket wall and the cup bottom wall is rounded or chamfered.

16. The adsorption cell according to claim 1, wherein a height of an individual pill defined by the largest distance between the top and the bottom is less than 5 mm, preferably less than 2.5 mm.

17. The adsorption cell according to claim 1, wherein the wall thickness of the cup bottom wall and the jacket wall is less than 300 micron, more preferably less than 150 micron.

18. The adsorption cell according to claim 1, wherein a height of the jacket wall of the cup is less than thickness of the pill which is defined by the greatest distance between the bottom and the top of the pill, so that neighboring cups of the stack of units do not contact each other.

19. A cluster comprising a matrix of adsorption cells according to claim 1, wherein the HTF channels of the individual adsorption cells are on both distal ends in fluid connection with a HTF manifold and wherein the refrigerant channels of the individual adsorption cells are on one or both distal ends in fluid connection with a refrigerant manifold.

20. An adsorption compressor, suitable for thermal wave operation, comprising:

at least one first cluster;

at least one second cluster;

a refrigerant circuit including:

a condensor having a condensor inlet and a condensor outlet;

an expansion valve;

an evaporator having an evaporator inlet and an evaporator outlet, the evaporator inlet being connected to condensor outlet via the expansion valve; and

an assembly of refrigerant valves that is configured to alternatively connect the refrigerant manifold of the

first cluster and the refrigerant manifold of the second cluster to the inlet of the condensor and the outlet of the evaporator;

a heat transfer fluid circuit including:

a first heat source having the function of a HTF heater;

a second heat source having the function of a HFT cooler and having a lower temperature than the first heat source;

a HTF valve assembly that is configured to be switched to conduct heat transfer fluid between the HTF manifolds of the at least two clusters and the HTF cooler and the HTF heater;

at least one pump for pumping around heat transfer fluid;

an electronic controller configured to control the HTF valve assembly to provide four modes of operation in which the heat transfer fluid can be pumped around:

a first mode wherein a single circuit of heat transfer fluid is arranged through the HTF heater, the first cluster, the HTF cooler, the second cluster and back in the HTF heater;

a second mode comprising two separated shortcut circuits: a first one in which heat transfer fluid flows from the HTF heater to the first cluster and returns to the HTF heater, and a second one in which heat transfer fluid flows from the HTF cooler to the second cluster and returns to the HTF cooler;

a third mode wherein a single circuit of heat transfer fluid is arranged from the HTF heater to the second cluster, to the HTF cooler and via the first cluster back again in the HTF heater; and

a fourth mode comprising two separated shortcut circuits: a first one in which the heat transfer fluid flows from the HTF heater to the second cluster and back in the HTF heater, and a second one in which heat transfer fluid flows from the HTF cooler to the first cluster and returns to the HTF cooler.

21. A method of cooling or heating comprising the following steps to be executed in any suitable order:

a) providing an adsorption compressor according to claim 20, b) heating in a first mode the adsorption material in a first cluster by gently pumping hot heat transfer fluid exiting from a HTF heater in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep decreasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the

elongated adsorption cells within the first cluster, wherein the adsorbed refrigerant is desorbed from adsorption material of the first cluster at relative high pressure, forced through check valve towards condenser, condensed and forced through expansion valve and left to evaporate and perform cooling action in evaporator,

c) cooling during step b) in a first mode the adsorption material in a second cluster by gently pumping cold heat transfer fluid exiting from a HTF cooler in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantial steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the second cluster, wherein the refrigerant is adsorbed by the adsorption material of the second cluster at relative low pressure, originating from the evaporator through check valve,

d) switching at a predetermined moment, to a second mode, cooling the adsorption material in a first cluster by gently pumping cold heat transfer fluid exiting from a HTF cooler in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep increasing heat profile in axial direction, i.e. a thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the first cluster, wherein the refrigerant is adsorbed by the adsorption material of the first cluster at relative low pressure, originating from the evaporator through check valve,

e) heating during step d) in the second mode the adsorption material in a second cluster by gently pumping hot heat transfer fluid exiting from a heater in a laminar flow through the heat transfer fluid channel of the adsorption cells of cluster, such that a substantially steep decreasing heat profile in axial direction, the thermal wave is maintained and gently pushed along the length of the elongated adsorption cells within the second cluster, wherein the adsorbed refrigerant is desorbed from adsorption material of the second cluster at relative high pressure, forced through check valve towards condenser, condensed and forced through expansion valve and left to evaporate and perform cooling action in evaporator;

f) switching back in the first mode and repeating steps a-f.

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